Pressure-Dependent Propagation of Streamers under Step Voltage in a long Point-Plane Gap in Transformer Oil

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ABSTRACT

The effect of pressure on positive and negative streamer propagation in a mineral transformer oil is studied in an 80 mm point-plane gap under step voltage. Increased pressure causes reduced stopping length for non-breakdown streamers, higher breakdown voltage, reduced background current, reduced branching in positive streamers and virtually no change in negative streamer shape. The velocities and acceleration voltages are close to being independent of pressure, indicating that the velocity controlling mechanisms take place in the liquid phase. Amplitude and frequency of small current pulses (probably small "reilluminations") during negative 1st mode is reduced with increasing pressure, but the effect on reilluminations during 2nd and 3rd mode is small in both polarities.

Index Terms — **oil, streamers, pressure, step voltage, velocity, stopping length, background current, reilluminations**

1 INTRODUCTION

MOST research on streamers under varying pressure has been done to improve the knowledge of streamer onset and propagation mechanisms. Small test cells with gaps in the range 2 – 7 mm have been used [1-12]. This limits the required voltage and has permitted the use of pressures typically up to 5 – 10 MPa. However, pressure dependence is also relevant for the operation of transformers subsea or at high altitude. This calls for studies in larger gaps. The present study addresses propagation in an 80 mm long point-plane gap. To keep the wall thickness of the large test cell within practical and economical limits, the range of pressures used was limited to 7.7 kPa to 1.7 MPa.

The small-scale studies have mostly used simple, pure liquids like cyclohexane [1-7], sometimes also with additives with particular electronic properties, n-hexane [8, 9], pentane [5] and tetraester [7], but silicone oil [5] and mineral transformer oils [5, 10] have also been investigated. The breakdown voltage, V_{BD}, has been found to increase with increasing pressure for both polarities [9, 10], as does positive onset [3-5, 8]. Negative onset has in one case been found to increase with pressure [11] and in another to be independent of pressure [3]. Increasing pressure causes reduced channel diameter in positive filamentary streamers [2] and for a given voltage it eventually suppresses propagation with the streamer stopping and disappearing [1, 2, 12]. Velocity is independent of pressure [2, 10], as is time to breakdown for streamers managing to cross the gap [10]. Increased pressure causes reduced branching. The almost hemispherical appearance of positive 2nd mode in mineral oil at atmospheric pressure becomes narrower and more pointed towards the cathode when pressure increases [6, 10]. In many liquids there are rapid pulsed phenomena ("reilluminations") from channels, causing light flashes and corresponding current pulses. Both their amplitude and frequency are reduced with increasing pressure [6, 7].

The present study does not address onset voltage, and channel diameter is superficially treated. The study is an extension of [13].

With increasing voltage, different propagation modes appear, with different appearance and increasing velocity that is liquid dependent, and several modes can appear at different times during propagation of one streamer [14-16]. The four modes commonly found with positive streamers have typical velocities 0.1, 0.7 - 3,

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3 – 20 and 50 – 400 km/s when counting from 1st to 4th mode [15]. In the oil used in this study, the shapes of the different modes are also very distinct. The mode distinctions are less clear for negative streamers [16], both in shape and velocity, but the streamers can similarly be forced into a corresponding mode classification with typical velocities 0.05 – 0.2, 0.4 – 2, 3 – 20 and 30 – 70 km/s with a distinct shape transition between 2nd and 3rd mode. It has been found that more pressure is required to suppress the faster modes than the slower modes [6]. Positive 1st mode requires very sharp anode tips to appear [17] and is not seen with the 0.7 mm diameter point used in the present study.

2 EXPERIMENTAL

The experiments were performed in an 80 mm point-plane gap in a 600 liters fiberglass vessel under pressures ranging from 7.7 kPa to 1.7 MPa. 7.7 kPa was the calculated hydrostatic pressure of the oil in the gap when there was vacuum above the oil. The point electrode was a 0.7 mm tin plated copper wire with the tip formed by breakdowns to a slightly flattened hemisphere. The point was placed on the earth side to allow for measurement of streamer currents. The diameter of the planar part of the high voltage plane electrode was 340 mm. A sketch of the setup is shown in Figure 1.

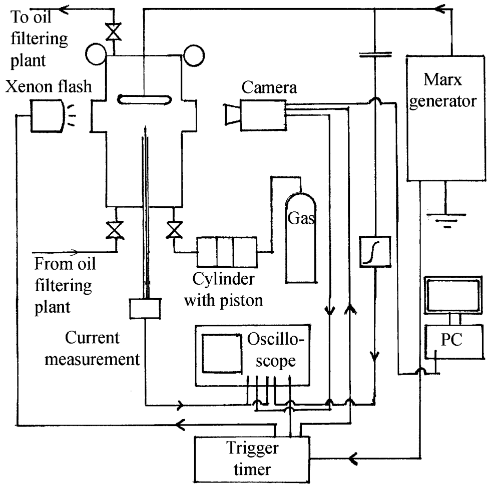

Figure 1. A simplified sketch of the setup.

To avoid changes in streamer propagation due to changes in voltage, a step voltage would have been ideal. The applied voltage impulse was a reasonable approximation for the duration of streamer growth with its 0.5 µs rise time and 1700 µs tail time (time to half of the peak value). At high voltages where very fast streamer modes dominated causing gap crossing in less than 1 µs, a significant part of the propagation happened during voltage rise.

The oil was NYNAS Nytro 10 XN, a naphtenic mineral transformer oil with 6 % aromatics. It was circulated through a degassing and filtering plant for 5 – 10 minutes after every breakdown. This would change only 30 – 60 % of the oil in the experimental vessel, but it would remove the carbonization from the gap.

The pressure was set with gas acting on a piston to avoid gas becoming dissolved in the oil. Evacuation was done via a separate vacuum line from the lid (not shown in Figure 1). The test cell was completely filled with oil. Pressure was measured with a mechanical gauge. The repeatability of the pressure setting was better than 5 kPa.

With the pressure vessel having two opposite viewports, the imaging was shadowgraphic with a xenon flash illuminating the streamer and the imaging being done with a DRS Hadland Imacon 468 camera with 6 functional frames with individual time and duration setting. 10 ns frame duration was the minimum possible, but 50 ns was the minimum used. Streamer channels thinner than the pixel resolution corresponding to 170 µm gap will still cause pixel darkening, but the diameter limit for detection is not known.

Voltage measurement was via an oil-filled capacitor differentiating the voltage signal, a coaxial cable and a passive integrator mounted directly on an oscilloscope input, the integrator restoring a scaled-down voltage signal.

Gap current was measured from the point electrode through a 50 Ω coaxial system with attenuators and overvoltage protectors, the protectors taking the current when breakdown occurred. The best sensitivity used on the oscilloscope (Tektronix DPO 4104) was 10 mA/div. Most oscillograms shown in this paper show the current on both a coarse scale and a much finer scale, in addition to the voltage trace.

As streamers can switch modes once or twice during propagation, the propagation velocity may vary considerably for one streamer. In this paper, the term "overall velocity" is used for the average velocity of one streamer during its propagation, while "average velocity" is reserved for the average over several streamers obtained by several impulse applications.

Velocities of streamers and their modes are calculated as the length difference between two image frames divided by the time between them. "Overall velocity" of breakdown streamers is calculated as gap length divided by time between a fixed shape feature early on the rising voltage (the inflection point) and breakdown. For non-breakdown streamers, the time start is the same, but length at stopping and time to stopping are measured from the frame sequences. With only 6 frames to cover the entire propagation, the time at stopping is uncertain and the corresponding uncertainty in non-breakdown overall velocity is estimated to 20 %.

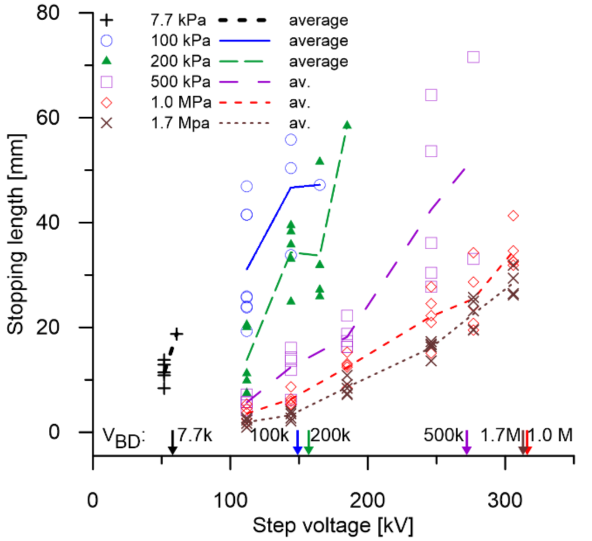

Figure 2. Stopping length of positive non-breakdown streamers. 50% breakdown voltages are indicated with arrows. k=kPa, M=MPa.

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For economic reasons, the number of voltages tested is low, as is the number of impulses per voltage, usually 5, but 3 at voltages filled in at the end because the original voltage selection was too sparse.

3 RESULTS

3.1 POSITIVE STREAMERS

As one might expect, non-breakdown streamers at a given voltage become shorter the higher the pressure is, as shown in Figure 2. The maximum stopping length before breakdown occurs increases with increasing pressure up to 500 kPa. Above, it decreases with increasing pressure. The 50 % breakdown voltage, V_{BD}, increases close to logarithmic with pressure (Figure 3). It is common to estimate the field along streamer channels as the inverse slope of the curves in figures like Figure 2. There is insufficient data for 7.7 kPa, but for 100 kPa it is 2.1 kV/mm and increases to about 7 kV/mm at 1 and 1.7 MPa at low voltages and 4.5 – 5 kV/mm at higher voltages giving the longest stopping lengths.

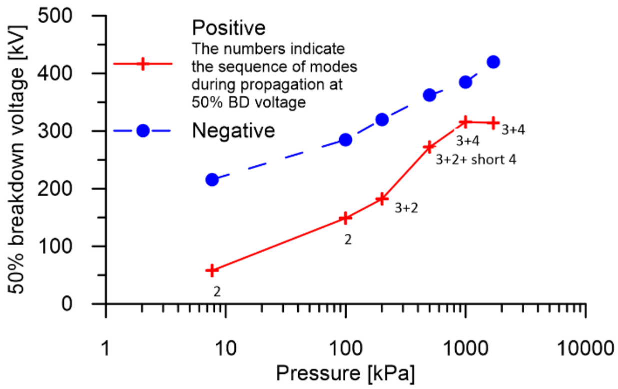

Figure 3. 50% breakdown voltage vs. pressure.

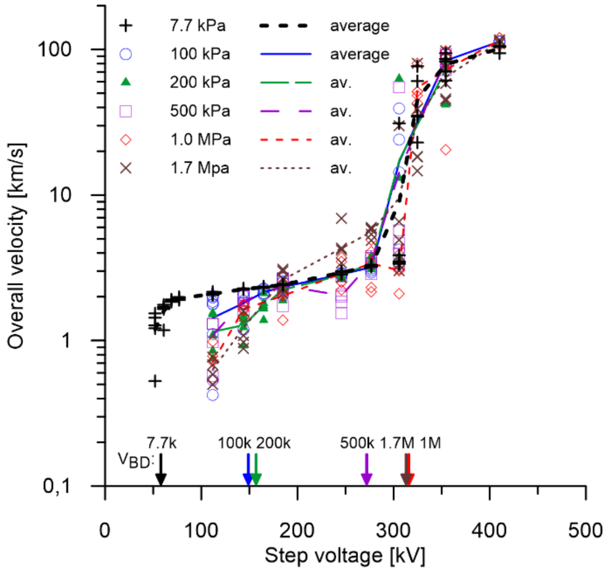

Figure 4. Overall velocity of positive streamers. Breakdown voltages are indicated with arrows. k=kPa, M=MPa.

Overall velocity is nearly independent of pressure (Figure 4), except possibly for non-breakdown streamers at low voltages. The "acceleration voltage", V_a, where the velocity vs. voltage curve suddenly increases faster, is also the same up to 500 kPa and is possible slightly higher at 1 and 1.7 MPa. The rapid increase in overall velocity with voltage above V_a is caused by the slow 2nd mode disappearing and being replaced by faster modes (3rd and most importantly 4th) [14, 15]. The eventual levelling-off of the velocity at even higher voltages happens when 4th mode has taken over the entire propagation.

Since the streamers at low voltages are 2nd mode, the same pattern is found for 2nd mode velocities as for overall velocities below acceleration voltage. 3rd mode velocity varied little with pressure, and no systematic variation was found for 4th mode. 3rd mode is found in the start of propagation at a sufficiently high voltage (about 150 kV) which varies little with pressure (Figure 5). A comparable value, 160 kV at 10 cm gap at 100 kPa, also in mineral oil, was found in [14]. At 1 and 1.7 MPa there were non-breakdown streamers even around acceleration voltage and these were entirely 3rd mode. Notice that 3rd mode appears well below the approximately 300kV acceleration voltage in this oil and setup.

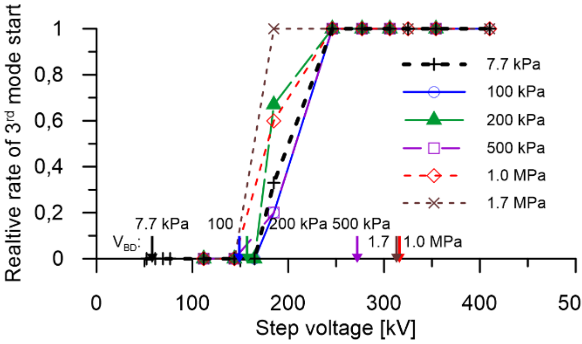

Figure 5. Relative rate of third mode start for positive streamers. Breakdown voltages are marked with arrows.

At a sufficiently high voltage, breakdown streamers are terminated with the very fast 4th mode, and the mode switch occurs earlier in the propagation with increasing voltage [14, 15]. In this setup, the lowest of the test voltages where this sometimes happened was 246 kV or lower up to and including 200 kPa (Figure 6). This is well above V_{BD} at these pressures, but it is also well below V_a. For 500 kPa and higher, 4th mode appearance voltage and V_{BD} were identical. At 1 and 1.7 MPa, breakdown at V_{BD} happened by switch to 4th mode when 3rd mode streamers had reached about 40 % of the gap length.

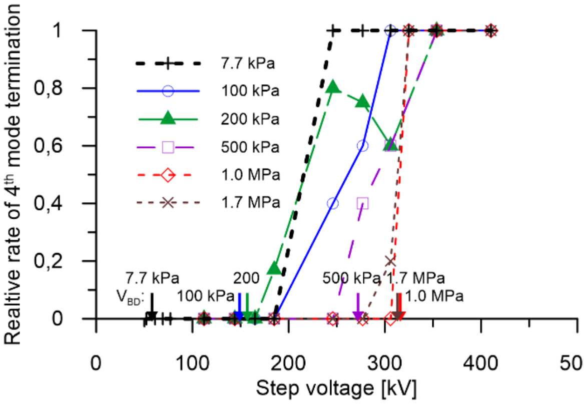

Figure 6. Relative rate of 4th mode termination of positive streamers. Breakdown voltage is marked with arrows.

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The degree of branching of the streamers is reduced with increasing pressure, as seen in Figure 7 and Figure 8.

There is a current running while a streamer propagates. This consists of a small, continuous background current with superimposed fast pulses (typical duration 10 ns) of typically some amperes amplitude. The pulses are known as "reilluminations" as they are associated with bright light flashes along one or more channels (only one channel at a time). For non-breakdown streamers, background current is reduced with time. For 2nd mode breakdown streamers, it is more constant and can sometimes even increase a little at the end of the propagation. The background current at 6 μs has been selected for comparison, and it decreases with increasing pressure (Figure 9).

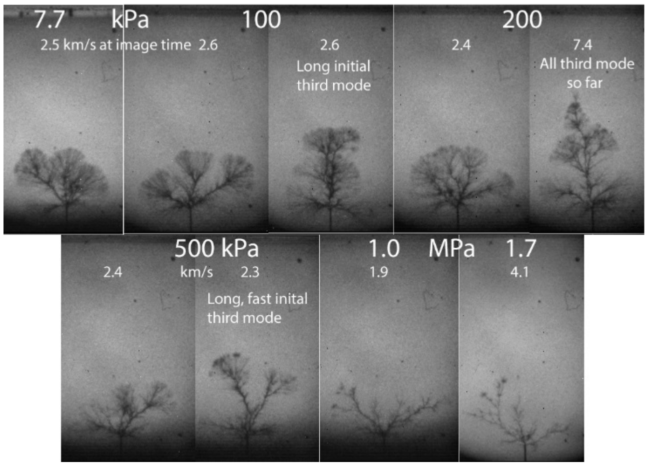

Figure 7. Positive streamer shapes at 5.5 μs, at 306 kV. The branching is reduced with increasing pressure. The entire gap is shown. Velocity at image time is indicated.

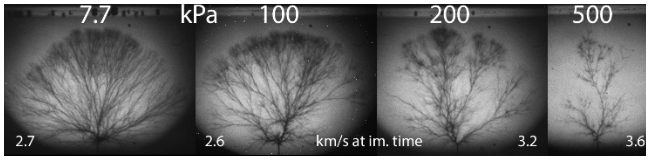

Figure 8. Shape of long, positive 2nd mode streamers at 25 μs, shortly before breakdown, at 277 kV. Long 2nd mode streamers did not exist at higher pressures. The branching is reduced with increasing pressure. The entire gap is shown. Velocity at image time is indicated.

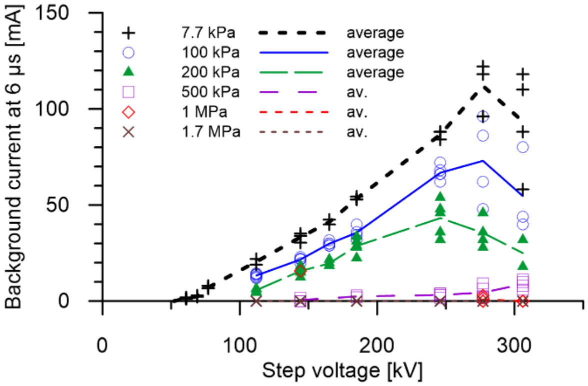

Figure 9. Background current at 6 μs for positive streamers.

When streamers start in 3rd mode and switch to 2nd mode, there are separate groups of reilluminations for the two modes. Between the two groups there is a pulse-free interval which decreases with increasing voltage and with increasing pressure (compare Figure 10 and Figure 11) and eventually disappears when pressure and/or voltage becomes high enough. There seems to be a slight tendency for the frequency of 2nd mode reilluminations to be reduced and their amplitude to increase very slightly with increasing pressure in breakdown streamers, until 2nd mode disappears (Figure 10, Figure 11). When increased pressure caused streamers to switch from going to breakdown to stopping, the maximum amplitude of reilluminations was reduced, mainly because the largest amplitudes took place in the last, now removed, part of the propagation. At voltages above V_a where 3rd mode breakdown streamers switch directly to 4th mode, the frequency and amplitude of reilluminations in 3rd mode do not seem to be pressure dependent (not shown in any figure, but except for polarity and somewhat larger amplitudes and shorter times quite similar to negative streamers in Figure 20).

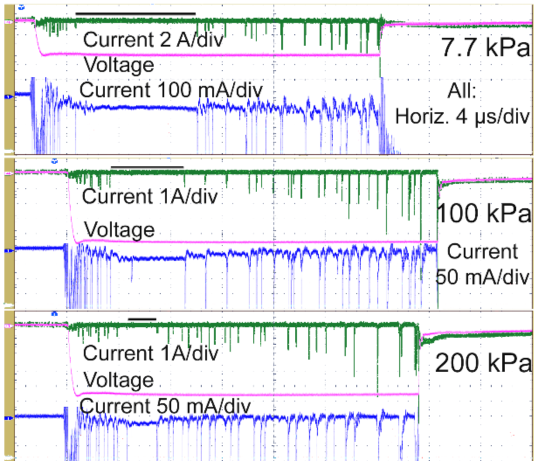

Figure 10. Reilluminations of positive streamers starting in 3rd mode and continuing in 2nd mode, at 246 kV. Black bar marks pulse-free interval.

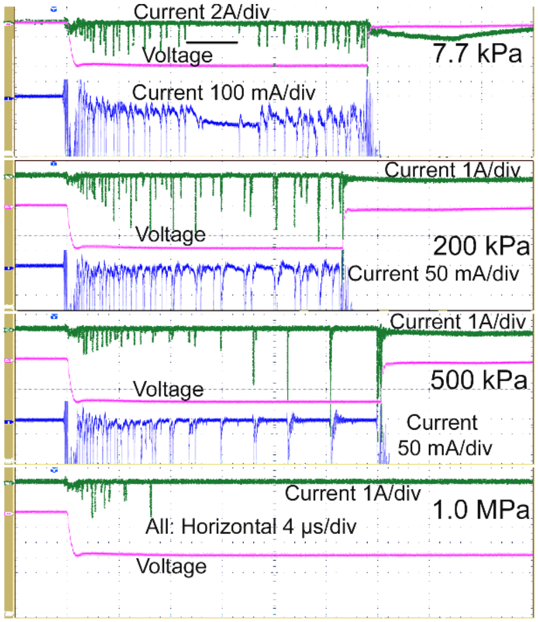

Figure 11. Reilluminations of positive streamers at 306 kV. All streamers shown start in 3rd mode, and up to 500 kPa they eventually switch to 2nd mode and continue to breakdown. The streamer at 1 MPa stops and dies in 3rd mode. A horizontal black bar marks pulse-free interval at 7.7 kPa.

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3.2 NEGATIVE STREAMERS

Like for positive streamers, stopping length of negative streamers at a given voltage is reduced with increasing pressure (Figure 12). The maximum length of stopping negative streamers just below V_{BD} does not seem to be consistently reduced with increasing pressure, but here the small number of voltages used may contribute to the impression. The estimated field along the channels seems to approach 2.5 kV/mm as the stopping length increases with voltage, at all pressures. It is much higher at low voltages where the stopping length is short, especially for high pressures.

Overall velocity is independent of pressure within the statistical uncertainty caused by the few tests (Figure 13). The same is the case for the velocities of all four modes: some small variation could be seen, but it was totally unsystematic with the pressure variation. 3rd mode streamers first appeared at the same test voltage of 313 kV at all pressures. This is below V_{BD} for all pressures at or above 200 kPa. Like for positive streamers, V_{BD} increases close to logarithmic with pressure and is considerably higher than positive V_{BD} (Figure 3).

Negative streamer shapes at a given voltage were close to independent of pressure, provided the streamer had not stopped, as shown for 1st to 4th mode in Figure 14, Figure 15, Figure 16 and Figure 17. Unfortunately, for 1st and 2nd mode, few of the frames were taken at the same time position.

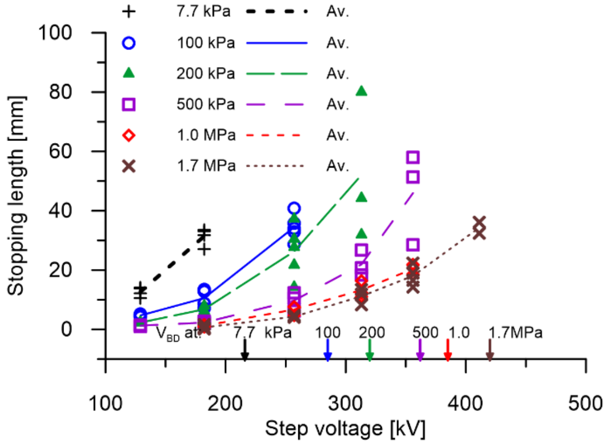

Figure 12. Stopping length of negative non-breakdown streamers. 50 % breakdown voltages are indicated with arrows.

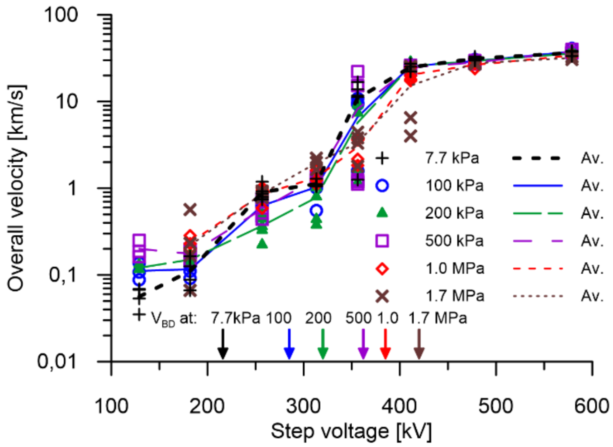

Figure 13. Overall velocity of negative streamers. 50 % breakdown voltages are indicated with arrows.

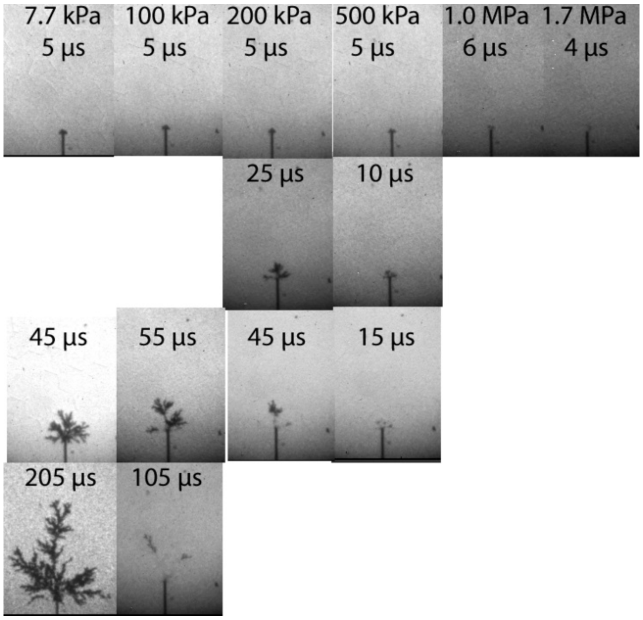

Figure 14. Negative 1st mode streamers at 182 kV. Vertical columns show the same streamer developing. Frames are missing to the right because the streamer has stopped and died out. The entire gap is shown.

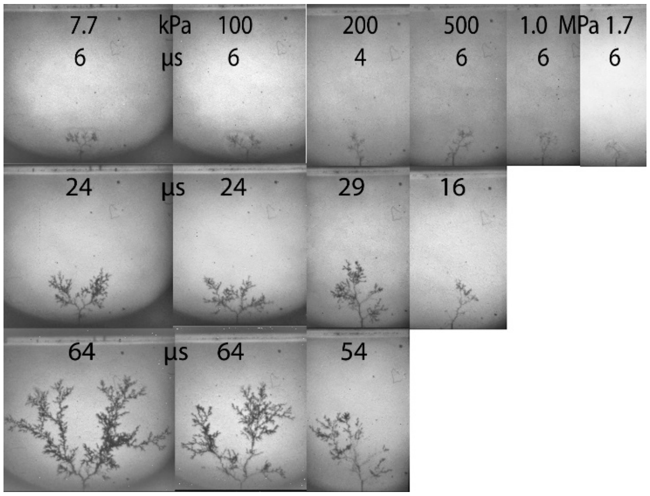

Figure 15. Negative 2nd mode streamers at 313 kV**.** Vertical columns show the same streamer developing. Frames to the right are missing because the streamer has stopped and died out. The entire gap is shown.

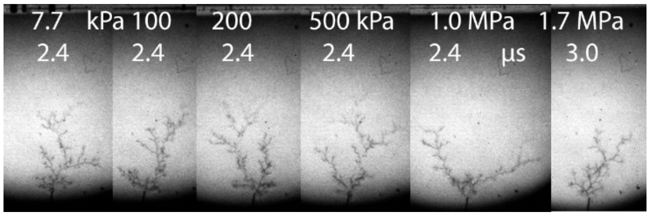

Figure 16. Negative 3rd mode streamers at 411 kV**.** Entire gap is shown.

Like for positive streamers, the current consists of a continuous background current and superimposed pulses called reilluminations. The background current varies a little during the propagation, and generally decreases with time for non-breakdown streamers. The value at 6 µs is used for comparison. The higher the pressure is, the smaller is this current (Figure 18).

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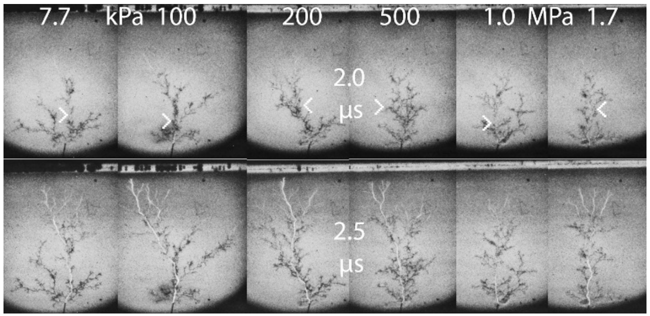

Figure 17. Negative 4th mode streamers developing out of 3rd mode streamers, 478 kV. Vertical columns show the same streamer. Approximate mode transition point is marked with < or > in the upper row. Entire gap is shown.

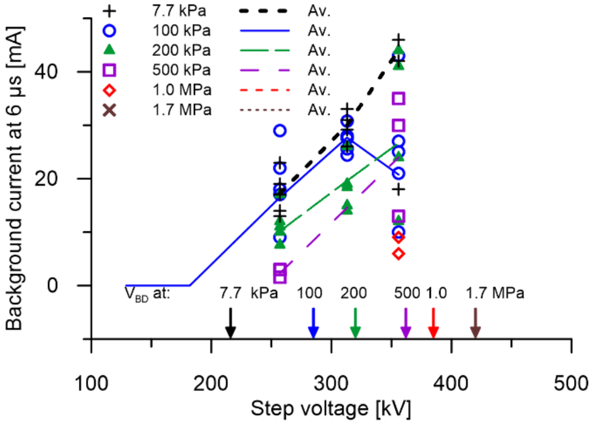

Figure 18. Background current at 6 µs for negative streamers. Breakdown voltages are indicated with arrows.

There are lots of current pulses during negative 1st mode, and they have corresponding light pulses [16]. While the typical "reillumination" is from 0.5 A and upwards, most of these pulses are much smaller. The light sensitivity of our camera is insufficient to discern the source of these pulses, but they are probably weak reilluminations. The current amplitude of these pulses is reduced with increasing pressure, e.g. at 182 kV they were 20 – 600 mA at 7.7 kPa, falling to 20 – 200 mA at 200 kPa and 20 – 50 mA at 1 MPa. Generally, increasing pressure caused reduced pulse rates, although up to 200 kPa there was little effect on the rate during the first 20 µs. For non-breakdown streamers, the duration of the pulse trains was loosely related to the time to stopping, usually being shorter but now and then a little longer. The total number of pulses decreased with increasing pressure because shorter stopping length and constant velocity meant shorter lifetime.

Negative 2nd mode reilluminations tend to appear with less regularity than positive 2nd mode reilluminations. The frequency of "proper" reilluminations in the range larger than about 0.3 A, and their amplitudes, do not differ noticeably at different pressures, but at low pressures, there are in addition many more small pulses with amplitude 0.1 A and lower. An example is shown in Figure 19 where the initial reillumination cluster belongs to 3rd mode start. In streamers propagating most of the time in 3rd mode before switching directly to 4th mode, no pressure dependence is seen in reillumination frequency and amplitude, provided the propagation has not stopped (Figure 20).

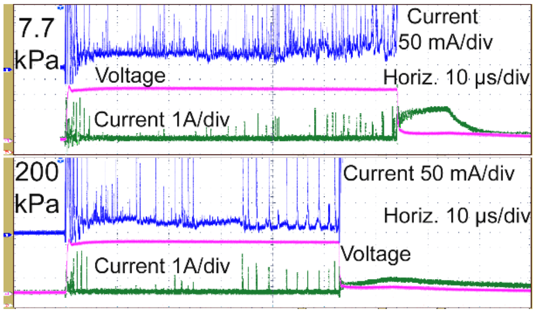

Figure 19. Reilluminations and small pulses in negative streamers starting in 3rd mode but propagating most of the time in 2nd mode.

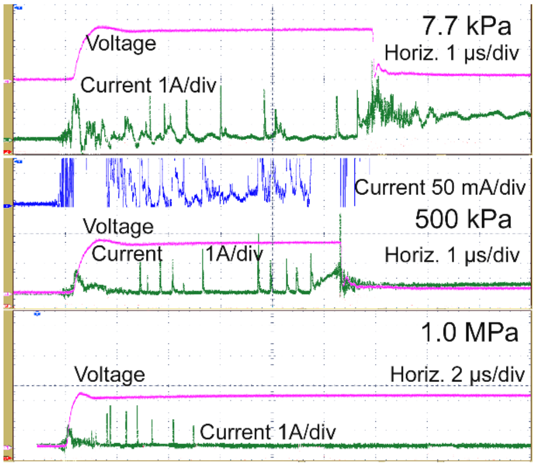

Figure 20. Reilluminations in negative 3rd mode streamers at 356 kV. For the two streamers going to breakdown, there is 4th mode the last approximately 0.5 µs.

4 DISCUSSION

The results confirm that what has been observed in gaps of less than 10 mm is also valid in an 80 mm gap. For both polarities, streamer velocity is close to independent of pressure [2, 10], and consequently so is time to breakdown. Increased pressure suppresses propagation and causes streamers to stop and disappear [1, 2, 12] and also causes positive streamers to become less branched and more pointed [6, 10], like what is seen in Figure 8. Negative streamer shape is said to be influenced by pressure [11], but elsewhere it is also stated that the pressure influence on negative streamer shape is less pronounced than for positive streamers [10]. In the present study, pressure had no effect on negative streamer shape except that the streamer collapses and disappears when it is stopped. The reduction in pulse frequency and amplitude in negative 1st mode is as described in [6].

It is generally agreed that the streamer consists of a head where there is ionization in front of a more or less conductive channel of gas and plasma. Charges separated at the head is channeled to the electrode through the channel, which also modifies the field at the head by bringing much of the point electrode potential out to the head. There is some controversy concerning the location of the ionization. One opinion is that it is collisional and happens in gas already made by heating at the tip, another opinion is that it happens by collisions within the liquid phase at the same time as many more collisions heat the

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liquid and eventually evaporate it. The fact that velocity, acceleration voltage and third mode onset voltage do not change with pressure is a strong indication that this takes place in the liquid phase. What is discussed in the following is mainly in favor of the liquid possibility.

The velocity being pressure-independent indicates that the velocity controlling processes must take place in a medium not notably affected by the pressure, i.e. the liquid phase of the oil, as previously noted in [14]. The rate of ionization in collisions (avalanching) would be a good candidate for a velocity controlling process. Thus, this most likely means that electronic avalanching is taking place in the liquid. The streamer length at a given voltage is highly pressure-dependent as seen in Figure 21 and Figure 22, and thus most likely involves the effect of pressure on the channel which is gas and plasma filled and which is the only compressible medium present. Where there are enough voltage points for reasonably good statistics, the stopping length seems to be reduced as P^{-1}, where P is the pressure.

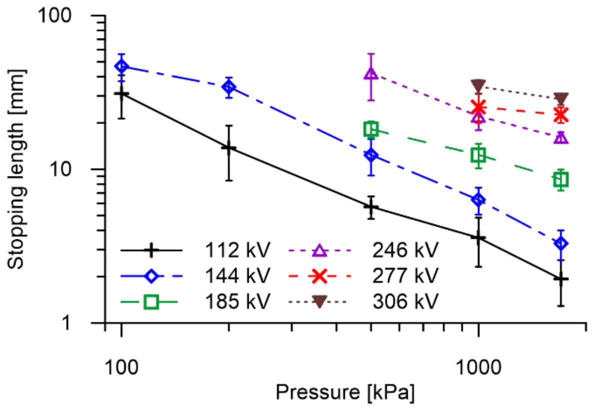

Figure 21. Stopping length vs pressure for positive streamers at various step voltages. With standard deviations.

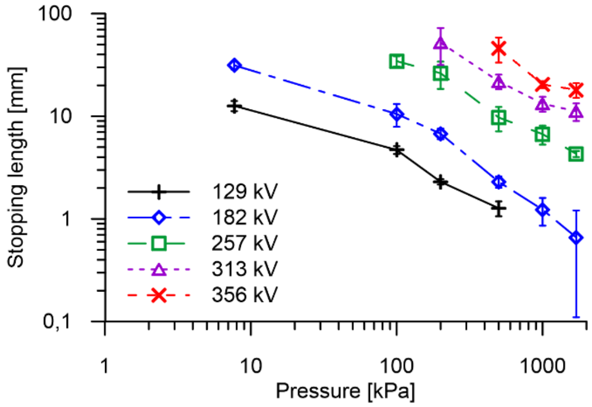

Figure 22. Stopping length vs pressure for negative streamers at various step voltages. With standard deviations.

For sub-millimeter positive 2^{nd} mode non-breakdown streamer channels, it has been shown that heating in the streamer head causes outward oil inertia, continuing for a while in the channel behind the head [18]. Collapse follows when the outward inertia no longer overcomes the hydrostatic pressure in the oil ("Rayleigh bubble mechanism"). Resistive heating caused by the current had some limited effect in maintaining the channel up to 0.5 MPa. Channel formation is probably similar for the long streamers, but for these the current seems to contribute more to maintaining them. This is partly because current from a lot of streamer tips is collected into a few main channels due to branching, and partly because of the energy conversion from reilluminations. The main branches of positive streamers for both 2^{nd} and 3^{rd} mode could be up to about 0.5 mm thick at 0.1 MPa, being much thicker than the roughly 10 µm [18] of a typical single 2^{nd} mode non-reilluminating positive channel. At increasing pressure, the diameter and length were clearly reduced, and above 0.5 MPa the lifetime of positive 2^{nd} mode streamers was rapidly reduced. The systematic increase and possible subsequent decline in channel diameter with position expected from the Rayleigh bubble process is not seen for these thick channels. The camera resolution was insufficient to determine detailed shape of the thin channels. The effective heating power of the complete streamer channel structure due to background current can be estimated from the field inside channels (estimated from Figure 2 and Figure 12), and the background current shown in Figure 9 and Figure 18. The heating due to the brief reilluminations in single channels is estimated to be several orders of magnitudes higher than the heating due to background current, assuming the same field and the observed reillumination current. Neither occurrence rate nor current amplitude of the reilluminations were noticeably affected by the pressure in 2^{nd} or 3^{rd} mode. (3^{rd} mode streamers are expected to be more conductive and thus have a lower internal field). Thus, the energy supplied to a reilluminating channel is largely independent of pressure and smaller diameter should be expected at increased hydrostatic pressure since the gas pressure energy content is PV (pressure times volume) and seems not to increase.

Whatever the nature of the channel expansion is, the energy for forming the channel is what the avalanches in the streamer head can get out of the actual electric field at the streamer head through collisional processes. This energy does not increase with pressure, except the field may increase somewhat due to reduced mutual shielding when the fine branching becomes reduced. Consequently, initial outward oil inertia should be independent of pressure, but it works against the hydrostatic pressure, so the maximum radius of the "Rayleigh bubble" should decrease with increasing pressure, resulting in a thinner channel already at the formation just behind the head.

For all pressures, most of the fine branching seen early in the propagation has vanished later. Only comparatively few more important branches propagate further again being a starting point for new fine branching. This indicate that the life of the fine branches may be more like the life of a Rayleigh bubble.

It has formerly been found that the degree of branching of positive streamers increases when the liquid has some constituents with low ionization potential [19-21], like polyaromatics [22], presumably by favoring avalanche start backwards toward the streamer head by e.g. photo-ionization in a wide sector around a streamer tip. Nonetheless, reasonably extensive fine branching has also been seen in a liquid with a supposedly negligible aromatics content but with high viscosity [15]. Like in [10], it is also clear that increased pressure causes decreased branching, at least in a liquid like Nytro 10XN with

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normally very extensive branching. It has also been assumed that the dense branching suppresses 4th mode and ensures a high V_a because mutual shielding lowers the field in front of the streamer, but increased pressure causes increased voltage for start of 4th mode termination despite removing the branching, and additionally there is no reduction in V_a.

Negative streamers are strange: streamer shape for a given mode is close to the same through all liquids tested in [16], and here it is found that increased pressure has virtually no effect on streamer shape or velocity, either. Breakdown voltage only increased a factor of 2 for negative streamers compared to 5 for the positive ones over the investigated pressure range.

It has already been shown that small reilluminations during 1st mode get reduced in amplitude and frequency with increasing pressure. However, reilluminations in 2nd and 3rd mode in both polarities are hardly affected by pressure except of course that reilluminations at the end of propagation are removed when increasing pressure causes a switch from breakdown to non-breakdown streamers. This happens despite increased pressure causing reduced channel diameter, at least in positive 2nd mode streamers.

The significance of the "gap" in reilluminations between initial 3rd mode and later 2nd mode when both modes are present is unknown. It becomes smaller and eventually disappears with both increasing voltage and increasing pressure.

5 CONCLUSIONS

Results from sub-centimeter gaps are confirmed to be valid in an 80 mm gap. For both polarities, streamer velocity and acceleration voltage are close to independent of pressure clearly indicating that the velocity controlling mechanisms take place in the liquid phase. The length a streamer grows at a given voltage is markedly reduced with increasing pressure. Therefore, breakdown voltage increases with increasing pressure. In an oil where positive streamers show extensive fine branching, the degree of branching is reduced with increasing pressure. Negative streamer shape was virtually independent of pressure.

There seems to be only small or no effect on reilluminations in 2nd and 3rd mode in both polarities, except a reduction in number when pressure causes reduced stopping length. Reilluminations during negative 1st mode get reduced amplitude and repetition frequency with increasing pressure. Pressure increase also causes reduced continuous background current.

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