Pressure Dependent Propagation of Positive Streamers in a long Point-Plane Gap in Transformer Oil

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Abstract— **The propagation of positive streamers in a naphtenic transformer oil in an 80 mm point-plane gap has been investigated under an impulse voltage being close to a step voltage and under pressures ranging from 0.1 to 1.7 MPa. As has previously been found in short gap experiments of 1 – 7 mm in various liquids, increasing voltage leads to shorter stopping length of non-breakdown streamers and higher breakdown voltages while the velocity is close to independent of pressure. The "acceleration" voltage from which streamer velocity rapidly increase with increasing voltage is also close to pressure independent. It is argued that this indicates that the processes determining velocity must take place in the liquid phase at the streamer head while conditions in the channel determines the stopping length of non-breakdown streamers**.

Keywords—oil, streamer, pressure, velocity, point-plane, breakdown.

I. INTRODUCTION

Knowledge of streamer processes in oil under pressure may have practical application, e.g. for insulation of subsea electronics or transformers for offshore oil or offshore wind power. It may also help in the attempts at understanding the processes taking place in streamer formation and propagation. Most of the existing work seems to be directed toward the latter task. Common to most of the available studies is a short electrode gap, for point- to plane gap and impulse voltage typically somewhere in the range 1 -7 mm [1-9]. While most of the work has been done in pure liquids like cyclohexane, n-hexane, toluene, pentane or cyclooctane, there are also examples of studies in transformer oils [1, 2] or silicone oil [2]. Some of the work has mainly used the effect of pressure on onset for illuminating streamer mechanisms [4-7]. One study using a long gap (80 mm) has looked at the effect of *reduced* pressure [10, 11].

The present work is concerned with the propagation and breakdown in a commercial transformer oil in a much longer gap, 80 mm. It has not even been attempted to identify onset voltages, partly because the shape of the point electrode cannot be kept well-defined through the many breakdowns. The polarity reported here is exclusively positive, and results will be compared to findings from the many short gap studies. Of practical reasons due to the large size of the test cell, the pressure is limited to 1.7 MPa, while many of the short gap experiments have had maximum pressure in the range 5 – 9 MPa.

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II. EXPERIMENTAL

An 80 mm long point-plane gap had a point electrode consisting of a 0.7 mm tin plated copper wire as ground electrode and a plane with 340 mm diameter as high voltage electrode (Fig. 1). The gap was situated in a fiberglass pressure vessel with steel end flanges and a volume of 600 liters. Breakdowns shaped the end of the wire to a somewhat flattened hemisphere. The pressure was set with gas pressure from a cylinder, the gas pushing a piston separating the gas and oil to avoid gas adsorption in the oil. The pressures applied were 0.1, 0.2, 0.5, 1.0 and 1.7 MPa. The pressure was measured with a mechanical gauge, and repeatability of the pressure setting was better than 5 kPa.

The oil was the naphtenic transformer oil NYNAS Nytro 10 XN. There was a degassing and filtering plant with filters for removing carbon particles. The oil was circulated through this plant for 5- 10 minutes after each breakdown. During this time only 20 – 40 % of the oil in the tank was circulated through the filter, but the procedure removed the oil with carbon from breakdowns out of the gap.

The tank had two viewports opposite to each other, and an image converter camera (DRS Hadland Imacon 468) took time-resolved shadowgraphic frame image sequences. Illumination was by a xenon flash. The number of frames available was 6, and timing of each frame could be set individually. Minimum possible exposure time was 10 ns, but 50 ns was the shortest exposure used.

Ideally, streamer propagation should take place under constant voltage, requiring a step voltage. The best approximation we could get was an impulse voltage from a

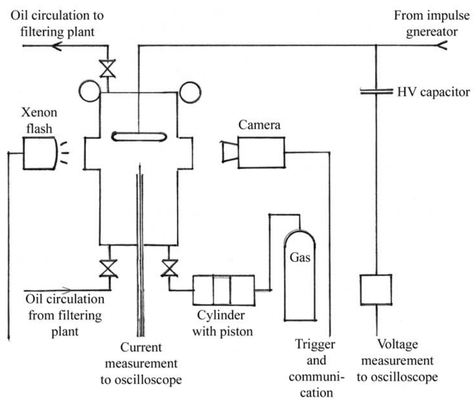

Fig. 1. Simplified sketch of the setup

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Marx generator with a nominal rise time of 0.5 µs and a tail time to half the maximum value of 1700 µs. As the propagation always took less than 80 µs, the constancy was usually fulfilled except at high voltage where very fast streamers crossing the gap in about 1 µs had a significant part of the propagation taking place during the voltage rise. The voltage was measured with a measuring capacitor differentiating the voltage signal and a passive integrator mounted directly on the oscilloscope (Tektronix DPO 4104) restoring a scaled down voltage signal [12]. There were 5 impulses for each voltage – pressure combination.

The "overall" streamer velocity of non-breakdown streamers was measured as maximum length divided by time to maximum length, as measured from the image frame sequences. With only 6 frames to cover the entire propagation using a presetting of the timing based on expected time to breakdown, the precision in measured time to maximum length is poor, leading to an estimated uncertainty in the velocity of about 20 %. "Overall" velocity of breakdown streamers was measured as gap length divided by time to breakdown. The time zero reference point was at a fixed point so early on the voltage curve that none of the streamers would have inception there. The error this would cause would be significant (about 20 %) only for the fastest streamers at high voltage, causing breakdown in 1 – 2 µs. The term "*overall velocity*" is used to keep it separated from actual velocity which may very well vary during propagation. "*Average velocity*" means the overall velocity averaged over the 5 impulses for a voltage – pressure combination.

III. Results

Below breakdown voltage, streamers would propagate and then stop. As one would intuitively expect, the stopping length at a given voltage was shorter the higher the pressure was, as seen in Fig. 2 . Accordingly, the breakdown voltage increased with increasing pressure, as seen in Fig. 3.

It is more intriguing that the velocity is close to independent of pressure (Fig. 4). Even the *acceleration voltage*, i.e. the voltage where the velocity suddenly starts to increase substantially more rapidly with increasing voltage due to a gradual shift towards faster modes, varies little with pressure. For the two highest pressures, breakdown voltage and acceleration voltage are the same within the resolution of the relatively coarse voltage steps used in this study. Even the velocity of the *individual modes* observed (second, third and fourth) showed little pressure dependence.

Second mode streamers have considerably branching at atmospheric pressure in this oil, but the degree of branching is reduced with increasing pressure. An example is shown in Fig. 5.

IV. Discussion

The pressure-independence of the velocities is in line with what has been observed in short gaps in various oils [1, 2], and it suggests that the processes controlling the velocity must take place in the liquid phase since the oil is close to incompressible, as also observed in [13]. Since the channel is gaseous and more or less plasma-like and hence should be affected by the pressure, these processes are likely to be the electronic processes in the streamer head area which are necessary for the streamer existence in the first place.

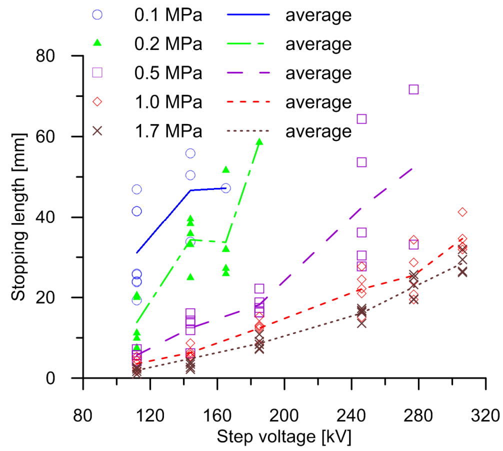

Fig. 2. Stopping length of non-breakdown streamers

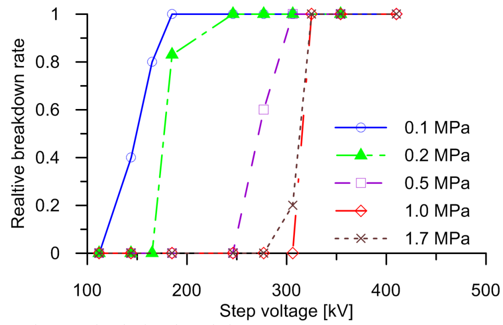

Fig. 3. Observed relative breakdown rate

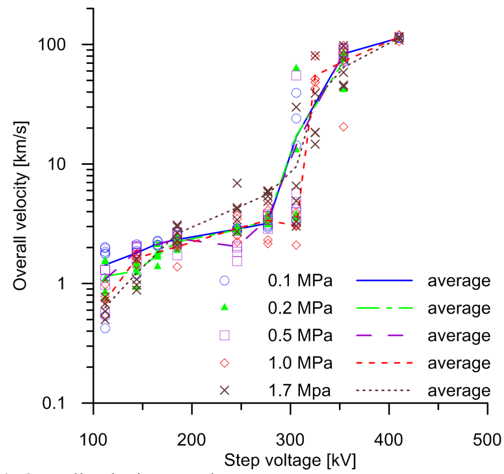

Fig. 4. Overall velocity vs voltage.

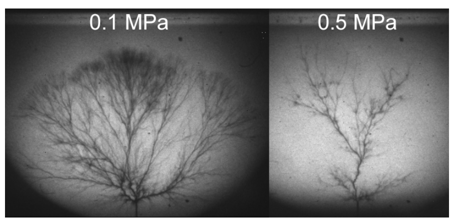

Fig. 5. Second mode streamer branching at 277 kV. 0.1 MPa (left) and 0.5 MPa (right). Long second mode streamers did not exist at higher pressures.

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Likewise, as also observed in short gaps [2, 3] the non-breakdown streamer stopping length is very pressure dependent. This indicates that the stopping length is governed by processes in a pressure-sensitive medium, which can only be the channel.

The pressure independence of the velocity also causes the acceleration voltage to be close to pressure-independent.

Reduced branching with increasing pressure, with the resulting streamer looking to be more directed towards the plane electrode, has previously been observed in Shell Diala D [1].

An energy argument can be used for the pressure dependence of the stopping length. With increasing pressure, forming and maintaining a channel should require more energy. The only instantaneously available energy source is the field in the gap. For a given voltage, this is independent of pressure, so the necessary increased energy to evaporate liquid under pressure is not available. This fits well with a small-gap study which found that the diameter of the "filaments", i.e. channels, was reduced with increased pressure [2].

The increase in breakdown voltage with increasing pressure has also been observed in short gaps [1], and is a natural consequence of the stopping length becoming shorter with increased pressure.

V. Conclusion

Increasing pressure causes stopping length and degree of branching to decrease, and breakdown voltage to increase. However, the velocities are close to pressure independent. This confirms that observations previously done in various short gap studies are valid in longer gaps, too. Furthermore, also the acceleration voltage is close to pressure independent. These observations suggest that the processes controlling the velocity must take place in the oil at the head of the streamer channel, while the stopping length of non-breakdown streamers must be controlled by processes in the channel and the limited energy available to be fed into channel formation by the streamer head.

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