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Discharges and Streamers Properties in Dielectric Liquids under Various Temperature

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Abstract—This paper presents partial discharges and streamers characterizations on 3 dielectric liquids under variation of wide temperature range, i.e.: aromatic hydrocarbon dibenzyltoluene, synthetic ester and halogenic perfluoropolyether liquids. Results indicate distinct behaviors among these liquids under highly divergent AC sinusoidal and impulse electric field. Dibenzyltoluene demonstrates excellent feature in suppressing discharges even at elevated temperature. In synthetic ester, positive discharges appeared to be less numerous but extremely high up to several nC in amplitude are strongly related to the further breakdown. Streamers inception voltage which denotes the initial discharges properties and streamer propagation velocity varies from several m/s up to order of km/s, show less dependency to temperature instead of the intrinsic characteristic of liquid itself. These pre-breakdowns phenomena constitute interesting information in planning and selecting insulation liquids and analyzing fundamental mechanism during the operation and maintenance for HV utility applications.

Keywords—partial discharges, streamers, divergent field, dibenzyltoluene, synthetic ester, perfluoropolyether

I. INTRODUCTION

Dielectric liquids have been used as insulation in high voltage (HV) applications since decades ago. Their low viscosities and self-healing properties attribute advantage features than other materials such as solid. In practice, the embedment of dielectric liquids with other dielectric materials such as solid and gases that involve thermal, electrical, mechanical, and chemical reactions and stresses result in complex behaviours. These gradually or even instantly reduce the quality of dielectric liquid as insulation when exploited beyond their limitations.

Discharges and streamers phenomena mark the pre-breakdown characteristics of dielectric liquids as response to the dynamics of transient and energy displacement. The nature of imperfection of surface and inhomogeneous of material, boundary interface between/among materials, impurity and contaminants within the proximity enhanced by the fluid motions are favourable for the generation of enhanced divergent field. Intrinsic pre-breakdown properties of liquids are strongly related to the chemical and physical properties of liquids such as molecular structures, applied temperature and pressure, space charges generation, etc.

It is essential to have comprehensive understanding of these behaviours and properties especially in the HV applications where the dielectric materials are required to have higher reliability, higher load-ability, longer durability and

more eco-friendly. Sufficient knowledge of the pre-breakdown characteristic will be an advantage to precise and conform to the actually applications of dielectric liquids in HV operations. Since breakdown and discharges properties of liquids are directly dependent on the features of pre-breakdown streamers, it is of great interest to investigate these phenomena under high temperature (HT) which may occur under temporary heavy/overload or faulty circumstances. This paper focus on partial discharge (PD) and streamer measurements under HV AC and impulse divergent fields. In addition, investigating streamer inception and propagation versus temperature is also of great interest for better understanding the physical mechanisms involved in streamers, since the liquid/vapor transition (i.e. creation of a vapor cavity or filament) constitutes a basic condition for streamer development in liquids.

II. DIELECTRIC LIQUIDS AND EXPERIMENTAL SET UP

A. Dielectric liquids

Liquids used in this study are the aromatic hydrocarbon dibenzyltoluene (DBT), synthetic ester (SE) and halogenic perfluoropolyether (PFPE). Liquids properties are shown and compared in Table 1 below.

Table 1. Dielectric Liquids Properties

Properties	M/DBT	Synthetic Ester	PFPE
Commercial product	Jarytherm® DBT	MIDEL® 7131	Galden® HT 270
Chemical name	Dibenzyltoluene	Pentaerythritol	Perfluoropolyether
Molecular formula	C ₂₁ H ₂₀	C ₂₅ H ₄₀ O ₈	CF ₃ [OCF(CF ₃)CF ₂] _n (OCF ₂) _m OCF ₃
Molecular weight [g/mol]	272.384	472.61	1550
Density [g/cm ³]	1.0±0.1	1.0±0.1	1.86
Kin. viscosity at 25°C [mm ² /s]	42.94	53.56	11.70
Pour point at 760 mmHg [°C]	-38.5 to -32.8	-60	-66
Boiling point at 760 mmHg [°C]	390	250	270
Vapour pressure at 25°C [mmHg]	0.0±0.4	0.0±1.4	< 10 ⁻²
Enthalpy of vaporization [kJ/mol]	62.8±0.8	80.3±3.0	97.34
Fire point [°C]	230	316	-
Self-ignition point [°C]	500	> 260	-
Flash point [°C]	200	260	-
Specific heat 20°C [kJ/kg·°C]	1.60	1.902	0.963
Thermal cond. 20°C [W/m·°C]	0.128	0.147	0.065
Dielectric strength [kV/mm]	> 57 ¹⁾	> 54 ¹⁾	15.7 ²⁾
Dielectric constant at 25°C	2.66	3.28	1.94
Water saturation at 20°C [ppm]	-	2700	< 20

¹⁾ Breakdown under AC quasi uniform field at 0.39 mm gap 50°C

²⁾ Breakdown under AC quasi uniform field at 2.54 mm gap 25°C

Jarytherm® DBT is constituted by a mixture of dibenzyltoluene isomers [1]. It is mainly used as heat transfer liquid with excellent HT properties: high thermal stability, boiling point, flash point, and low toxicity. The similar chemical composition liquids Jarylec® DBT and mono/di-

benzyltoluene (M/DBT) used as capacitor liquid [2-5]. MIDEL® 7131 is a product of M&I Materials [6]. Synthetic ester (SE) liquid is biodegradable with high fire point and low pour point which is mainly used in HV applications e.g. transformers up to 433 kV. This liquid has superiority maintaining stable operation under highly water content. Golden® PFPE is a heat transfer fluid produced by SOLVAY [7]. This liquid has high thermal stability up to 270°C with no flash or fire point and no auto-ignition point, compatible with metal, plastics and elastomers.

B. Partial discharge measurement set up

PD characteristics of materials is important for HV applications, since they indicate practical maximum limits in terms of electric field or voltage, and also demonstrate how the material resists to deterioration. Most of time, PD tests are done in arrangements typical for a particular application (e.g. winding samples for transformers or rotating machines). PDs addresses localized dielectric breakdown phenomena, indicating the high electric field withstand ability of dielectric.

In dielectric liquids, PDs usually start from high field regions such as sharp electrode edges, boundary of dielectric materials (triple-points), where the electric field can be very divergent. Therefore, to replicate these conditions, PD measurements were carried out using a point-plane geometry with tip radius of curvature was 2.0 μm and point-plane distance 10 mm, in an open cup stainless steel testcell as shown in Fig. 1. This testcell allowed PD measurements up to 25 kV.

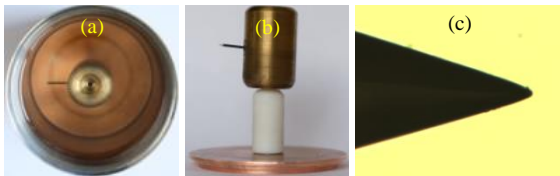


Fig. 1. Point-plane electrode system: (a) open testcell, (b) point electrode with support and (c) microscopic view of point with radius 2 μm

Two dielectric liquids were set in these measurements: DBT and SE. The average water content of DBT prior to measurements at initial new condition was 13 ppm and 72 ppm in SE. Saturation limit of SE is 2700 ppm, which correspond to 2.7% saturation at room temperature (RT). Saturation level of DBT is unknown.

Measurement set up is shown in Fig. 2, where PDs were measured with a Phase Resolved Partial Discharge (PRPD) analyser (Power Diagnostix™ ICM system). HV supply was provided by a PD-free transformer fed by a low-noise and low-distortion power amplifier. A careful shielding of all components (including heating circuit, temperature sensors, etc.) allowed reducing the noise level to a very low value about 0.1 pC. Measurement system was calibrated using a standard 5 pC calibrator. To avoid recording noise, the rejection level of PDs was fixed to 0.2 pC.

The PDs number, charge, phase position, and average current were recorded during periods of 1-minute duration under constant voltage. Series of 10 PD recordings of 1-minute duration were obtained at each applied voltage and temperature. PDs inception voltage (PDIV) were derived from plots of PDs count versus voltage. Since no clear PDs extinction threshold could be observed at low voltage, PDIV was arbitrarily defined as the voltage producing 10 PDs (of either polarity) per minute. This PDs number (10) was chosen since it lead to an acceptable statistical significance of the

corresponding voltage, during 1 minute duration tests. In plots, the PDIV presented here corresponds to the mean values of these 10 measurements.

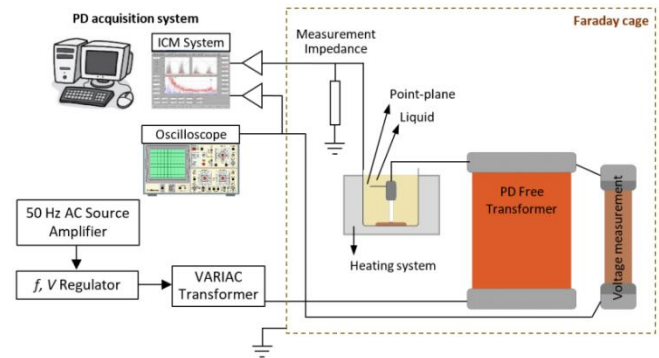


Fig. 2. Dielectric liquids PD measurement set up

C. Streamer measurement set up

Streamer measurements, i.e. streamer inception voltage (SIV) and streamer propagation were carried out with a special design testcell that can contain liquids at HT as shown in Fig. 3. Temperature is regulated via a digital temperature controller with a 30 W heater placed at the bottom part of the testcell and monitored with a thermocouple. In this system, the variations of the liquid temperature at different locations within the testcell did not exceed $\pm 5^\circ\text{C}$. Testcell body was made with PTFE (polytetrafluoroethylene) and sealed with O-rings made of Viton®. Thus, maximum temperature of testcell is limited to 250°C.

The stainless-steel point electrode had an initial tip radius of curvature $r_p = 2.5 \mu\text{m}$, plane electrode diameter was 10 mm, and gap distance d was fixed to 5 mm. The upper part of the testcell was connected to a gas management system, allowing to apply either vacuum, or dry Nitrogen gas at the desired pressure.

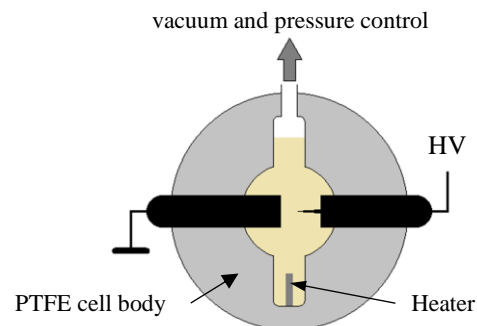


Fig. 3. Schematic drawing of the high temperature streamer testcell

After filled in the testcell, liquids were degassed under vacuum for >12 hours. Then dry nitrogen at 0.1 MPa was introduced prior to measurements, in order to avoid liquid oxidation and prevent the risk of fire. Pressure was regulated to remain at 0.1 MPa during measurements at any temperature variations.

Streamer measurements set up is shown in Fig. 4. A high voltage impulse generator based on a push-pull 65 kV solid state switch (Behlke® HTS 651-03-GSM) was used. Rectangular high voltage impulses of positive polarity were obtained, with adjustable duration t_{HV} , i.e.: 1 μs for positive streamers and 2 μs for negative streamers. A 2 k Ω resistor was placed in series to limit the current in the case of breakdown. The rise and fall times of the HV impulse were 150 ns. To

study positive streamers, the point electrode was connected to high voltage and the plane to ground, and conversely for negative streamers. Time-resolved shadow-photographs of streamers were obtained with a gated image intensifier. The intensifier's gate was opened after an adjustable delay t_d after the rise of voltage. Different image magnifications were used either to detect streamer inception with a high resolution (about $5\ \mu\text{m}$), or to observe streamer propagation over longer distances.

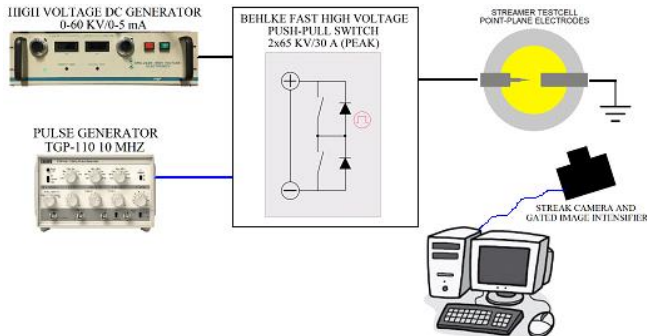


Fig. 4. Streamer shadow-photographic measurement set up

All measurements results were obtained with the same point electrode in order to obtain stable conditions and therefore results are comparative even the liquid nature or temperature was changed. Great care was taken to avoid the occurrence of breakdown (that would induce point electrode modification) during measurements. This was achieved by reducing the HV pulse duration t_{HV} in such a way to avoid streamer propagation reaching the plane. At the end of measurements, the point showed a negligible erosion (its tip radius r_p increased from $2.5\ \mu\text{m}$ to about $3\ \mu\text{m}$).

Streamer inceptions were detected from visualization using the highest magnification in order to record every streamer. In several cases, their size can be rather small, down to about $10\ \mu\text{m}$ in diameter. Since streamer inception usually gets a random character, a statistical method was used. Series of 20 shots were applied at fixed voltage, and the number of streamers initiated was noted. From this series, the inception frequency was calculated and plotted versus voltage. Voltage was increased in steps, ranging from 0% to 100% inception frequency.

III. MEASUREMENT RESULTS

A. PD measurements in DBT

Typical PRPD recordings in DBT under open-air (23°C) at atmospheric pressure are shown in Fig. 5. PDIV of DBT at RT is 15 kV. Most of discharges occurred at negative polarity, even when voltage was raised well above PDIV.

Both the discharges number and amplitude increase as the applied voltage goes up. Negative discharges with very low amplitude (less than $5\ \text{pC}$) accumulate around the voltage peak (approx. 270° phase angle). Very few small amplitude positive discharges were also detected, starting from 20 kV (< 5 discharges/minute and $< 1.1\ \text{pC}$). These measurements are quite similar to those already obtained in Jarylec® C101 [8], which chemical composition is close to Jarytherm® DBT (mixture of M/DBT isomers).

In DBT, this behaviour is observed over a large voltage range, from 15 kV to 25 kV in measurements. This shows the exceptional good properties of liquids of the benzyltoluene family, producing PDs of very small amplitudes. In contrast,

in many other liquids such as esters, mineral oils, or silicon oils, large positive PDs up to several nC in amplitude appear in the same conditions [8]. This explains why benzyltoluene liquids (Jarylec® C101) are used in impregnated capacitors, where PD inception is a key parameter for reliability.

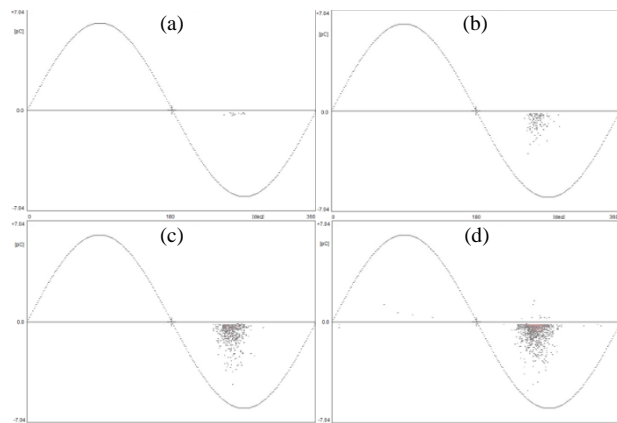


Fig. 5. Typical PRPD pattern in DBT at room temperature 23°C for applied voltage: (a) 15 kV, (b) 16 kV, (c) 17 kV and (d) 19 kV

When the temperature was raised, the discharges number decreases, and then PDIV increase. Fig. 6 shows typical PRPD patterns at RT and 80°C for $V = 20\ \text{kV}$, i.e. slightly above PDIV. PDIV at 80°C is 19 kV, i.e. 127% of PDIV at RT.

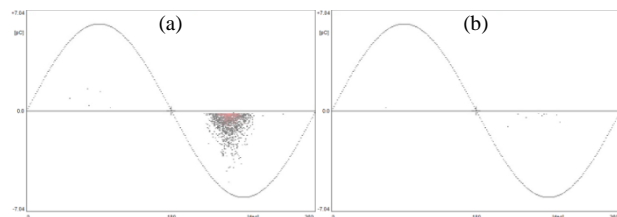


Fig. 6. Typical PRPD pattern in DBT for applied voltage 20 kV at: (a) room temperature 23°C and (b) 80°C

The mean charge and number of PDs recorded during 1-minute in DBT at various temperatures are shown in Fig. 7. Total negative discharges counts drops significantly from 1664 discharges/minute at RT to 17 at 80°C , with mean charge between $-1.4\ \text{pC}$ to $-0.9\ \text{pC}$, and PD current $I_{PD} = 24\ \text{pA}$ to $0.12\ \text{pA}$. The same behaviour on positive discharges was also observed at high temperature. At 80°C , positive discharges were hardly detected i.e. < 10 discharges count/minute throughout the applied voltage range up to 25 kV.

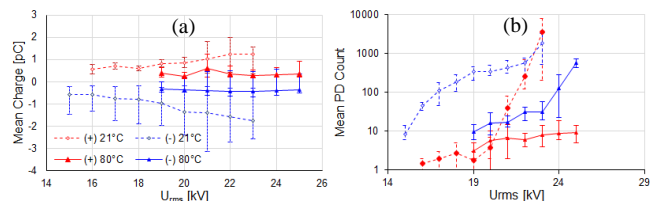


Fig. 7. Positive and negative discharges at 21°C and 80°C in DBT: (a) mean PDs charge and (b) PDs count per minute

B. PD measurements in SE

Fig. 8 shows the typical PRPD pattern in SE at 21°C RT under open-air atmospheric pressure. PDs pattern in SE is totally different from that of DBT. With high detection sensitivity ($\pm 13.9\ \text{pC}$ scale in Fig. 8a), negative discharges with much higher amplitude as in DBT are observed. However, if sensitivity is reduced (down to $\pm 1.39\ \text{nC}$ as in Fig. 8b), high amplitude positive discharges are now observed in SE, but not in DBT.

Negative PDs observed when voltage is positive on Fig. 8 (black arrows) are due to instrumental artefacts: large positive PDs saturate the measurement system, and false recorded signals correspond to oscillating overshoots (red arrows). Observation of PDs in SE requires two widely different sensitivities to properly record positive and negative discharges, which amplitudes differ by a factor about $\times 1000$.

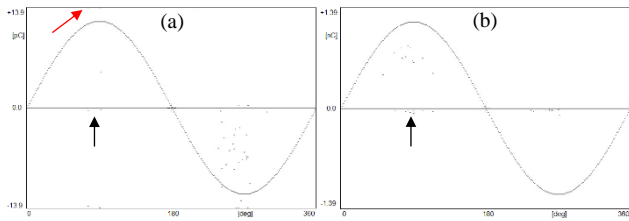


Fig. 8. Typical PRPD pattern in SE at room temperature 21°C for applied voltage: (a) 16.5 kV ($\pm 13.9\text{ pC}$ scale) and (b) 19 kV ($\pm 1.39\text{ nC}$ scale)

Fig. 9 shows typical PRPD patterns for constant applied voltage 17 kV at RT and 80°C , recorded with high sensitivity (a) to detect negative PDs and low sensitivity (b) to properly observe large positive PDs. Their number and amplitude increase when temperature was raised (up to 2.8 nC at 80°C). The corresponding PDIV of large discharges decreases with temperature. Negative discharges are not properly seen here due to low detection sensitivity.

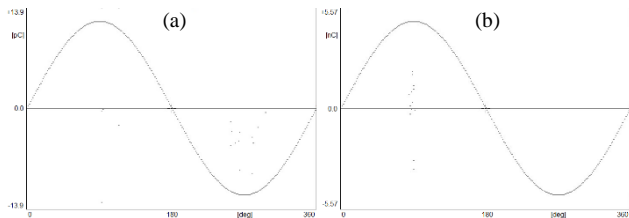


Fig. 9. Typical PRPD pattern in SE for applied voltage 17 kV at: (a) room temperature 21°C , max. scale $\pm 13.9\text{ pC}$; and (b) 80°C , max. scale $\pm 5.57\text{ nC}$

PDs data extracted from such measurements show the amplitude and count of large positive discharges. Their amplitude and number are promoted by temperature. If the PDIV of each polarity is quoted according to the same definition of 10 PDs/minute, positive PDIV is constantly higher than negative.

Under high sensitivity ($6.97\text{--}13.9\text{ pC}$ scale), measurements mostly refer to small negative PDs, which are more numerous, but some perturbations unfortunately exist due to false signals induced by large positives (see Fig. 8). Taking a value of 10 discharges per minute, the PDIV of small negative PDs can be estimated, yielding a decreasing trend with temperature. Considering low sensitivity measurements ($\pm 5.6\text{ nC}$ at 100°C), PDs current shows that few large positive PDs (10 discharges) can induce a much larger average current compared to numerous small negatives (70 discharges).

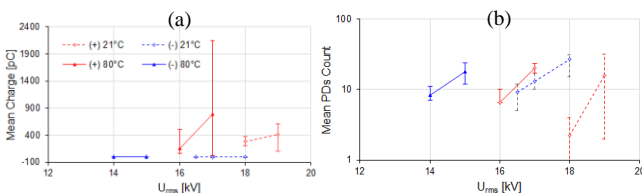


Fig. 10. Positive and negative discharges at 21°C ($\pm 6.97\text{ pC}$ scale for positive and $\pm 13.9\text{ pC}$ scale for negative) and 80°C ($\pm 1.39\text{ nC}$ scale for positive and $\pm 6.97\text{ pC}$ scale for negative) in SE: (a) mean PDs charge and (b) PDs count

C. Streamers measurements in DBT

1^{st} mode negative streamers at RT are characterized by a “bubble-like” shape as in Fig. 11a. The size of these negative

streamers grows as the voltage was raised. They developed reaching certain size, detach from the tip, and then collapse.

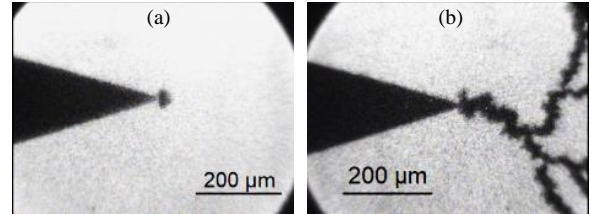


Fig. 11. (a) Typical negative streamer at 24°C , 20 kV , $t_{HV} = 2.0\ \mu\text{s}$, $t_D = 1.0\ \mu\text{s}$ and (b) positive streamers (2^{nd} mode) at 25°C , 26 kV , $t_{HV} = 1.0\ \mu\text{s}$, $t_D = 1.1\ \mu\text{s}$

Two different positive streamer modes (1^{st} mode and 2^{nd} mode) were observed depending on the applied impulse voltage, as also reported in other liquids under similar conditions [9,10]. At low voltage, 1^{st} mode streamers with “bubble-like” shape similar to those recorded in negative polarity (Fig. 11a) are observed. When the applied impulse voltage exceeds certain critical voltage (called V_2 in [9]), faster filamentary 2^{nd} mode streamers are now seen (Fig. 11b). At RT, 1^{st} mode positive streamers appear with 50% probability at $V_i = 23\text{ kV}$, and 2^{nd} mode streamers begin to emerge at 25 kV . The probability of 2^{nd} mode streamers increased while the 1^{st} mode streamers reduced when the applied impulse voltage was raised. The thickness of these filamentary positive streamers slightly grows as the temperature increases. Filamentary streamers at 200°C have a diameter about $50\ \mu\text{m}$ while at 100°C and RT it is nearly $20\ \mu\text{m}$ and $< 20\ \mu\text{m}$ [12].

D. Streamers measurements in SE

Negative slow streamers are characterized by a “bush-like” shape including thick branches, and propagating longer than in DBT (Fig. 12a). These streamers develop into longer and thicker filaments as the applied voltage increased.

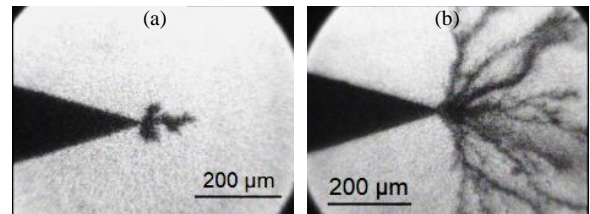


Fig. 12. (a) Typical negative streamers at 26°C , 26 kV , $t_{HV} = 2.0\ \mu\text{s}$, $t_D = 1.0\ \mu\text{s}$ and (b) positive streamer at 24°C , 24 kV , $t_{HV} = 1.0\ \mu\text{s}$, $t_D = 1.0\ \mu\text{s}$.

At higher temperatures (100°C and 200°C), “bush-like” negative streamers were still observable with slightly size growth as well as in DBT. However, when temperature was raised, inception measurements become rather unstable and more complicated in SE. When the liquid remained at 100°C in the testcell for several hours, streamer inception frequency tend to vanish: at $V = 30\text{ kV}$, the streamer inception frequency dropped from 100% down to 0%. Cleaning the testcell and electrodes, and filling it again with new liquid allowed to obtain streamers again. At 200°C , this process was even faster: it became impossible to observe streamers only after some 10 minutes, making reproducible measurements very difficult.

Positive streamers are mainly of 2^{nd} mode filamentary streamers. Fig. 12b shows typical positive streamer at RT. These streamers are characterized by numerous and long filamentary branches. There is no significant influence of temperature on streamer inception voltage at RT and 100°C .

The inception probability of positive streamers rises sharply to 100% within a narrow voltage range (2 kV range at 100°C).

E. Streamers measurements in PFPE

At RT, thick “bush-like” negative streamers were observed (Fig. 13a), similar to those in SE. The branches elongated as the voltage was raised from 23 kV up to 33 kV. When liquid was heated up to 100°C, negative streamers remained of 1st mode “bush-like” shape. In contrast with DBT and SE, temperature seemed to slightly reduce the size of “bush-like” streamer in PFPE. At 150°C there were no any branches and streamers get a “bubble-like” shape. Furthermore, 50% inception voltage of negative streamers were then increased when temperature was raised, while 10% probability voltage showed almost no change.

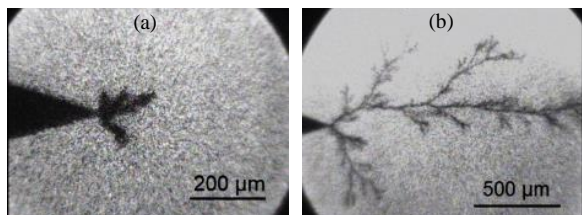


Fig. 13. (a) Typical negative streamer at RT, 30 kV, $t_{HV} = 800$ ns, $t_D = 400$ ns and (b) positive streamer at 100°C, 32.5 kV, $t_{HV} = 1.0$ μ s, $t_D = 500$ ns

Positive streamers are mainly of 2nd mode filamentary streamers. No slow 1st mode streamers were seen. Positive 2nd mode streamers have a different shape compared to DBT and SE, which consists of several main thick filaments, with several thinner side branches as in Fig. 13b. The applied voltage contribute to lengthen filaments as in DBT and SE, while temperature governs the thickness of filaments. The propagation velocity of these streamers (about 4 km/s) is more rapid than in DBT and SE. Inception probability shows large fluctuations at RT, and increases slowly on average versus voltage. At 100°C, streamers observed between 22 to 32 kV now nearly disappeared. At the maximum voltage investigated (35 kV), 50% inception probability was not reached [12]. At higher temperature, inception probability measurements were impossible due to the lack of streamers.

During measurements, PFPE liquid showed strong thermal convection and unexpected boiling tendency at 150°C (appearance of vapour bubbles, although the quoted boiling temperature is 270°C), setting the maximum temperature for streamers measurements. Visual recording also became blurred with less contrast disturbed by vapour bubbles emerging from the bottom of the testcell. The liquid turned cloudy after cooled down to RT. No clear explanation could be provided for these phenomena.

IV. DISCUSSION

In DBT, small negative and positive PDs, a few pC in amplitude, correspond to slow “1st mode” streamers that does not propagate far as in previous discussion [8]. Large positive PDs (not observed here) correspond to faster and longer “2nd mode” streamers. No large positive PDs were recorded indicates that the inception of “2nd mode” positive streamers under AC voltage in DBT are likely to occur at much higher voltage compared to other liquids. These measurements shows that in DBT temperature is significantly suppress PDs, both in discharges number and amplitude.

On the other hand, the fact that breakdown voltage of DBT under (quasi) uniform field decreases with temperature [11]

seems contradict to the PDIV increase with temperature. This comes from the rather contrast circumstances in both measurements. Under uniform field, the field at which breakdown (i.e. streamers) occur is in the range of 70 to 30 kV/mm [12]. In point-plane gap, maximum field calculated on the tip by Coelho’s formula [13] when PDs occurred, is extremely high. In DBT, it varies from 2.3 MV/mm (RT) to 3.8 MV/mm (100°C), and from 2.5 MV/mm (RT) to 2.2 MV/mm (100°C) in SE as shown in Fig. 14a.

In SE, PDIV corresponds to small negative and large positive discharges decreases with temperature where small negatives appear first. In DBT, PDIV corresponds to small negative discharges increases with temperature and large positives are not observed. Discharges recorded over a wider voltage range (up to 25 kV) remain at very low amplitude, mostly negative with few positives. At 100°C it is suggested that the actual PDIV is above 25 kV, since very few discharges were observed at this voltage.

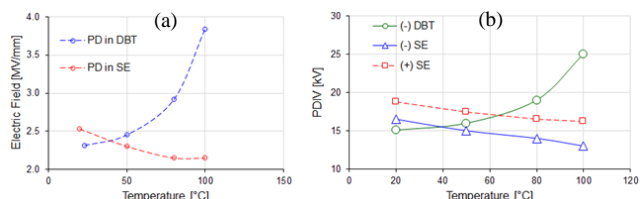


Fig. 14. Comparison between DBT and SE versus temperature: (a) electric field calculation on the tip from PDIV measurements and (b) PDIV.

The comparison of PDIV in Fig. 14b clearly shows that DBT has very good PD suppression properties at high temperature compared to SE. Furthermore, SE is dissatisfactory due to the presence of large positive discharges. Positive PDIV in SE shall be defined and treated differently since it only took few large positive discharges (< 10 PDs) to induce breakdown.

Under uniform field, it is known that a mean field of 30 kV/mm is unable to directly induce streamers in the liquid. It is generally considered that “defects” producing local field enhancement are responsible for discharge initiation: electrode surface defect, charged solid particles with permittivity and conductivity larger than the liquid. In point-plane, a very high field on the tip is able to induce streamers directly into the liquid. Under AC voltage, the influence of injected space charges (ions) prior to PD inception may also have an influence, but a much larger effect can be expected under point-plane gap, since the field is very divergent with very high field strength, promoting injection and reducing the actual tip field.

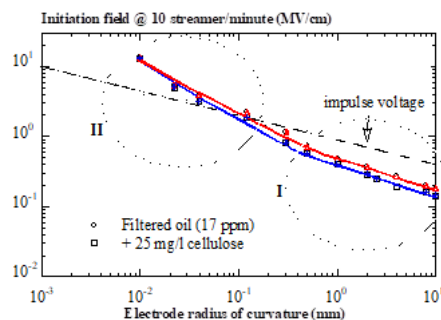


Fig. 15. Calculated streamer initiation tip field under AC (at 10 streamers/minute) versus electrode radius, and comparison with measurements under impulse voltage. Filtered mineral oil, and polluted with 25 mg/l cellulose (17 ppm water content) [14]

The influence of space charge on streamer inception under AC in point-plane geometry was already evidenced in mineral oil [14], by comparison with impulse voltage (Fig. 15) where space charge is nearly absent (injected ions have no time to move away from the electrode during the impulse rise time $< 1 \mu\text{s}$). In moderately divergent field (region I in Fig. 15), streamer inception fields under AC are logically lower than with impulse, since time duration of voltage is much longer. This is observed up to field values about 100kV/mm in mineral oil. Conversely, with sharp points (region II in Fig. 15) calculated AC initiation fields become larger compared to impulses, and this can be only explained by the influence of injected space charge. Calculated fields without influence of space charge overestimate the field, compared to the field actually present at the point under AC.

It was previously reported that the existence of 1st and 2nd mode streamers under impulse voltage depend on the point tip radius of curvature r_p [15]. Below some "critical radius" r_c (e.g. $r_c = 3 \mu\text{m}$ in pentane), both modes are observed, and above r_c only the 2nd mode is seen. The "critical radius" r_c in DBT is not yet known. The fact that two modes were seen indicates that the critical radius in DBT should be larger than the point radius used here (2.5 μm).

In DBT, streamer characterization shows quite similar results to those previously obtained of comparable chemical composition, Jarylec[®] (mixture of M/DBT) [16]. In positive polarity, two streamer modes were observed in Jarylec[®]. The difference of $V_2 = 12 \text{ kV}$ (gap distance = 6 mm), i.e. a much lower value compared to DBT in these measurements (25 kV) might be partly due to the fact of longer voltage rise time (150 ns) was used here, instead of 20 ns in [16]. It was previously reported that the measured threshold propagation voltage V_2 of 2nd mode streamers can be larger with longer rise time, due to the influence of injected space charge during the voltage rise [17].

Some degradation of the ester liquid probably occurred at high temperature, which either changed the liquid properties regarding streamer inception, or changed the conditions on the point. Since the formation of gels from esters was previously reported, we may suppose that a layer of gel on the point could modify the conditions of streamer inception. Further analysis is of course required to better understand these phenomena. The fact that only the 2nd mode was seen indicates that the critical radius in SE (not yet known) should be smaller than the point radius used here (2.5 μm).

Finally, it is obvious that in M/DBT liquids, the inception of filamentary streamers requires higher applied voltage as compared to many other liquids. In identical conditions of [17], 2nd mode streamers were observed above $V_2 = 6.7 \text{ kV}$ in mineral oil instead of 12 kV in Jarylec[®]. In this work, 2nd mode streamers observed in SE is at lower voltage than in DBT (20 kV in SE instead of 25 kV in DBT), with higher velocity. In PFPE, despite the inception of filamentary streamers is comparable to DBT, the probability was highly scattered. When inception probability in DBT already reached 100%, it only appeared to be 45% in PFPE at 33 kV, but streamers lead to breakdown in a short time due to much higher propagation velocity (positive streamers propagation velocity $> 4 \text{ km/s}$).

V. CONCLUSIONS

Pre-breakdown properties are essentially determined by the nature of dielectric liquids. The decreasing tendency of

discharges i.e. charges amplitude and charge numbers when temperature increases, higher PDIV, SIV and lower streamers propagation velocity as in DBT are favourable for dielectric liquids to maintain their feature as insulation particularly in heavy/over-load and faulty conditions resulting local hotspots.

High amplitude discharges even only few numbers positive discharges of 2nd mode filamentary fast propagation positive streamers as in SE and PFPE are strongly correspond to further breakdown in liquids.

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