Observation of Partial Discharge in Hexane under High Magnification

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ABSTRACT
Partial discharges are observed in hexanes by means of shadow photography under the application of dc voltages. A non-uniform field geometry is employed and the growth of cavities associated with partial discharges at a point cathode is photographed at 200 x magnification. A multi-frame photograph of the cavity and a simultaneous record of the partial-discharge current provide a detailed record of the temporal and spatial development of the discharge. Examination of these data suggest that electrostatic forces are of primary importance in driving the growth of the cavity near its inception.

INTRODUCTION
Electric breakdown of liquid dielectrics is preceded by the growth of a streamer in the liquid. Consequently, a great deal of research has been devoted to obtaining accurate descriptions of the conditions that influence streamer initiation and propagation. Despite this activity, no clear consensus has been reached as to the mechanism for the initiation of the discharge. Proposals put forward have included: electron avalanche [1], cavitation [2], and electrostatic forces acting on the dielectric [3, 4].

Studies of liquid hydrocarbons have shown that the form and the speed of propagation of negative streamers change dramatically as the streamer propagates across the electrode gap [5]. During its initial stages of growth, the negative streamer forms a complex structure sometimes referred to as a cathode bush. Both the extent and the dynamics of the bush have been shown to be highly dependent on the ambient pressure. (See, for example, Yamashita et al. [6] for a discussion of these effects.) A plausible description for this initial stage of growth has been presented by Watson and Chadband [7], who show it to be consistent with the propagation of a cavity within the liquid. Similar results are reported for partial discharges (PD): photographic and optical studies [1, 8, 9] have established a clear correspondence between the growth of a cavity in the liquid and discrete current pulses emitted from the cathode. In the present study, the conditions that exist near the threshold for PD activity are examined. For this, a record of the current waveform and a multi-frame photograph of the growth of a cavity at a point cathode are obtained simultaneously. Such
data allow detailed description of the temporal and spatial development of the cavity and provide a basis for the evaluation of models for the initiation of negative streamers.

The test gap consists of a steel needle and stainless steel rod separated by 3.2 mm. The electrodes are enclosed within a brass cell and are immersed in the test liquid. A well-characterized mixture of hexane isomers, ultra-pure grade hexanes (Alfa Products, product No. 13801\textsuperscript{4}), is used for this study. The liquid is used as received without degassing or further purification. The rod electrode is 0.4 mm in diameter and has a hemisphere of the same diameter at its tip. The rod is connected to a HV dc power supply through a 10 M\( \Omega \) resistor – the resistor is included in the circuit to limit the current in the event of breakdown – and appropriate filtering is provided to reduce pickup of power supply noise. The needle electrode is 1.0 mm in diameter; the needle point is approximately conical with an apex angle of 30° and the tip radius of a newly installed needle is \( \approx 1 \mu m \).

The optical resolution is improved primarily by mounting a microscope objective within the cell, close to the needle electrode. The total magnification of the optical system is 200\( \times \), and the optical resolution is sufficient to fully resolve objects < 2 \( \mu m \) in diameter. The image-preserving optical delay [9, 12] noted in the Figure delays the time of arrival of light at the camera by introducing a long optical path between the test cell and the camera: a delay of \( \approx 400 \) ns is thus provided. The optical delay offsets the electronic delay associated with the camera trigger and thus allows the framing sequence to begin much closer to, and for the 51 ns frame interval before, the onset of the current waveform. A continuous-wave argon laser is used to illuminate the needle tip. The synchronizer shown in Figure 1 contains a discriminator, used to set the trigger level, and provides trigger signals to the camera, the digitizing oscilloscope, and to a Pockels cell optical shutter. The optical shutter is normally closed and is included in the optical path to prevent continuous exposure of the camera’s image-converter tube.

A transimpedance amplifier, designed to provided a low-noise background against which low-level PD currents may be detected [13, 14], is used for these studies. The amplifier has three stages: a low-noise, broad-bandwidth, current-sensitive preamplifier and low-gain and high-gain buffer amplifiers. The combined system bandwidth is estimated to be 45 MHz and the equivalent noise current is 30 nA rms. The charge sensitivity of the system is estimated to be < 0.7 fC. Digital oscilloscopes having sampling rates of 400 and 100 Msamples/s were used during the course of these studies. It should be emphasized that the individual current pulses within a PD are much narrower than the impulse response time of the current detector and that the pulse shape is instrumentally determined: the intrinsic width of a single current pulse has been estimated to be on the order of 4 ns [1] while the impulse response of the measurement system has a width, \( \tau \approx 30 \) ns.

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The total charge emitted from the cathode during PD may be obtained by integration of the instantaneous current \( i(t) \):

\[
Q = \int_{-\infty}^{\infty} i(t) \, dt. \tag{1}
\]

Given the impulse response \( h(t) \) of the detection circuit, the observed signal is given by

\[
v(t) = \int_{0}^{t} i(t') \, h(t - t') \, dt'. \tag{2}
\]

Provided the pulse width \( w_p \) satisfies \( w_i \gg w_p \), the instantaneous current due to a single PD pulse at time \( t_p \) may be approximated by

\[
i(t) \approx Q \delta(t - t_p), \tag{3}
\]

where \( \delta(t - t_p) \) is the Dirac delta function. Upon substitution into Equation (2), this expression yields

\[
v(t) \approx Q h(t - t_p). \tag{4}
\]

The shape of the observed pulse is determined primarily by \( h(t) \) and, provided the amplifier is operated in a linear regime, the pulse amplitude and the area under the measured pulse profile are directly proportional to \( Q \) [15]. Thorough discussions of the methods used to calibrate the amplifier may be found elsewhere [11, 14].

Results reported by Pompili, Mazzetti, and Schifani [16] show pronounced conditioning effects in liquids: both the pulse-amplitude and time-separation distributions for PD change dramatically with time after the application of voltage. A similar effect was noted during the present studies: partial discharge activity decreased rapidly with time after application of HV. Since our primary interest in this study is the temporal and spatial development of PD at voltages near inception, the results presented here are obtained during the short time interval – typically the first 15 min – after the application of voltage to the cell. The voltages investigated ranged between 12.5 and 17.5 kV. Once the PD activity had decreased to an unacceptable level, voltage was removed and either the fluid was allowed to recover or the test cell was cleared and recharged with fresh fluid.

**PARTIAL DISCHARGE RECORDS**

Two examples of PD, obtained under identical experimental conditions, are shown in Figures 2 and 3. In each Figure, the current waveform and the numerically integrated current are plotted in the upper panels and the associated photographs are shown below. The frame sequence is indicated in each photograph, while the frame exposures, determined from the camera monitor pulse and an accurate measurement of the frame interval, are shown together with the current waveforms. The frame interval and exposure times are 512 and 102 ns respectively. The interference rings appearing in the photographs are an artifact due to the coherence of the laser light and may be disregarded.

The dynamical behavior of these structures is partic-
Figure 3.
Partial-discharge record. The current waveform and the integrated charge are shown in the upper two panels. Frame photographs of the point cathode are shown below. These data are obtained for an applied potential of 15.5 kV. The frame interval and exposure times are 512 and 102 ns, respectively, and the frame sequence is indicated in the photograph.

Figure 4.
Partial-discharge record obtained at 17.5 kV. The frame interval and exposure are 51 and 10 ns, respectively. The current waveform and the extent of the cavity are plotted in the upper panel.

The current waveform is relevant to describing the conditions at the initiation of the PD. In over 90% of the current waveforms, clear evidence of a continuous current occurs early in the waveform; the current waveform shown in Figure 2 is representative of this behavior. Furthermore, whereas the later current pulses tend to grow monotonically in amplitude, the first two pulses are frequently of comparable amplitude. Indeed, PD is observed that consist of only a double-pulse structure. Single pulse discharges were also detected; however, no evidence of cavitation could be seen in the associated photographs. These observations suggest that the current at the origin of the cavity growth differs from that at later times. For example, the motion of charge trapped in the liquid due

ularly intriguing and, although a great deal of variability is observed in their detailed structure, common patterns are observed. During its lifetime, the cavity first grows in size, then detaches from the needle, and finally breaks apart and collapses, moving away from the tip as it does so. The structure of the cavity appears to be approximately spherical at its inception and the cavity may grow by stable expansion, that is, by relatively uniform expansion, or by the growth in amplitude of instabilities in the cavity wall. Stable expansion is best shown by the structure appearing in Figure 2, whereas that shown in Figure 3 is an example of unstable expansion. Instabilities in the cavity wall may be due to hydrodynamic or electrostatic effects [7,17]. Indeed, upon close examination, evidence for the onset of finger-like projections may be seen in Figure 2. Stable expansion occurred less frequently at higher voltage and a preference for growth along the axis of the needle is noted for unstable expansion.
to the expansion of the cavity would give rise to a continuous current of the proper sign in the external circuit [18].

Another example of PD is given in Figure 4. These data are obtained at an applied potential of 17.5 kV and the frame interval and exposure times are 51 and 10 ns, respectively. Note that at this frame interval the first few camera frames precede the initiation of the current waveform. In this case, the sampling rate of the digitizer is 100 Msamples/s, which accounts for the rather coarse appearance of the current waveform. The data at hand allow an estimate of the time interval between the initiation of the current waveform and the onset of cavity growth. As shown, the current begins 51 ± 5 ns before the midpoint of the sixth frame, the first frame that shows clear evidence of the cavity. The estimated uncertainty in the position of frame six is ±8 ns; combining these uncertainties in quadrature yields 51 ± 9 ns and thus provides an upper bound of 60 ns. The extent of the cavity in the sixth frame, however, suggests that the time interval is likely to be significantly less. In the upper panel, the length of the cavity is plotted against the frame number and fit to a linear function. This procedure provides an estimate for the origin of the cavity that is nearly coincident with the initiation of the current waveform. This analysis was carried out on a sample of PD records obtained under identical experimental conditions and yielded similar results. We are reluctant to apply this correction, however, in the absence of a more accurate determination of the instantaneous rate of expansion of the cavity at its inception. The high correlation between the onset of cavitation and PD current noted here lends support to recent experimental results obtained in cyclohexane [1].

The frame photographs also provide an estimate of the rate of expansion of the cavity. Furthermore, since the expansion rate depends on the forces acting on the liquid, an estimate of the effective pressure within the cavity \( P_{in} \) may be obtained. For times near its inception, the cavity shown in Figure 2 is approximated reasonably well by an expanding sphere of radius \( r \). Further assuming inviscid incompressible flow, an expression for the instantaneous work done in expanding the cavity is given:

\[
P_{in} \, dv = P_{amb} \, dv + \frac{2S}{r} \, dv + \frac{3}{2} \rho r^2 \, dv.
\]

The terms include: the work done against ambient pressure \( P_{amb} \) and surface tension \( S \), and the kinetic energy imparted to the surrounding liquid. An estimate of the 6.6 × 10² kg/m³ and 1.8 × 10⁻² N/m, respectively [19]. For the conditions described, the kinetic energy term dominates and \( P_{in} = 0.4 \) MPa.

The required pressure may be provided by local heating of the liquid that may occur during electron avalanche, and by electrostatic forces. However, the form of the cavity suggests that the forces acting on the liquid are highly directional and that the gas dynamic pressure within the cavity is of limited importance. Furthermore, the pronounced pressure dependence of the streamer initiation voltage noted during impulse voltage testing of this material [6] is inconsistent with electron avalanche being the direct cause of the observed phenomena. The conditions for electron avalanche are satisfied when the electric field exceeds a critical value of \( E/N \) [20], where \( N \) is the number density, and over the range of pressures examined in that study the density of the fluid is essentially constant [19]. However, excess electrons in the liquid or at the interface between the electrode and the fluid would produce stresses in the liquid of the proper sign to produce the observed cavitation. Experimental results obtained from studies of cyclohexane [21] indicate that the charge density in the region near the needle tip is likely to be significant. These observations are further supported by electro-optic measurements in nitrobenzene that show charge injection prior to streamer initiation [22, 23]. We believe the present experimental work lends support to the results reported by Watson and Chadband [7] and suggest that electrostatic forces acting on the liquid are of primary importance in driving the growth of the cavity from its inception.

CONCLUSIONS

HIGHLY resolved photographs of the initiation of PD in liquid hexane are obtained. The cavity growth at a point cathode is nonisotropic, which suggests that electrostatic forces are of primary importance in driving its expansion. The onset of instabilities in the cavity wall is also suggested. The onset for partial discharge current is likely to be simultaneous with the growth of the cavity: an upper bound of 60 ns between the onset of current and the growth of the cavity is obtained.

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REFERENCES


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4 The identification of commercial materials and their sources is made to describe the experiment adequately. In no case does this identification imply recommendation by the National Institute of Standards and Technology, nor does it imply that the material is the best available.

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