Electrohydrodynamic Instability and Electrical Discharge Initiation in Hexane

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Abstract

An experimental technique is described that tests the hydrodynamic stability of the fluid boundary in a fluid-insulated system: A quasi-uniform field configuration is used and a pulsed, Nd:YAG laser is employed to create a micro-bubble at the surface of one electrode. The gap is pulse-charged and the laser is synchronized with the time-of-application of the voltage pulse. Under appropriate experimental conditions of voltage and laser pulse energy, the bubble evolves to produce full electrical breakdown by the onset and propagation of instabilities in the bubble surface. Experimental data obtained in hexane are presented.

Introduction

In recent years, laser-based techniques have been used to examine electrical breakdown in fluids. These methods have, typically, relied on the strength of the electric field that may be achieved in the focused beam of a pulsed laser to ionize the fluid and produce a volume of ionized plasma within the fluid. In a few of these studies, pulsed laser systems were used to trigger an electrical discharge in a charged gap; such studies were undertaken to further explore the nature of spontaneous breakdown in fluid-insulated equipment [1] and to evaluate techniques for switching high voltages [2, 3]. In the cases cited, electrical breakdown in the full gap was thought to proceed by 1) damage to the integrity of the fluid, for example, by modification of the local charge density, and the subsequent failure of the insulation [1] and 2) by conduction through an ionized channel produced by the laser [3]. Relatively high pulse energies were required to trigger the discharge by these methods: at approximately 80% of the self-break voltage a minimum energy of 30 mJ was needed to trigger a discharge [1].

The work presented here was undertaken to examine the feasibility of triggering an electrical discharge in a fluid-insulated gap by means that are, in principle, much less invasive: by, essentially, perturbing the electrode-to-fluid interface. In virtually all cases reported to date, breakdown in a self-breaking gap proceeds by the onset and propagation of a prebreakdown streamer across the gap; the origin of the streamer is, invariably, at or adjacent to the electrode surface. Evidently, the conditions at the electrode-to-fluid interface play a critical role in the initiation and early development of the electrical discharge. Put succinctly, the question posed here is: Can the native mode-of-failure of an insulating fluid, that is, the onset and propagation of a surface-launched streamer, be triggered externally? The demonstration described below suggests that, indeed, a prebreakdown streamer can be externally triggered and that this method is distinguished most notably from earlier reported results by the energy required to trigger the discharge: The results presented show that laser pulse energies as low as 0.5 mJ are sufficient to trigger the discharge.

Experiment

The two-electrode gap used for these studies is shown schematically in Fig. 1. The geometry of the test gap closely resembles the coaxial configuration used by Guenther, et al. [3] and commonly employed in gas-phase triggered switches [4]. The high-voltage electrode is 19 mm in diameter and has a 10-mm radius-of-curvature. The grounded, planar electrode is 20 mm in diameter and has a 2-mm, central aperture for passage of the pulsed laser beam. The electrode separations used here ranged between 3 and 4 mm.

The electrode-fluid interface is perturbed by a photoacoustic pulse that is produced by light from a pulsed, Nd:YAG laser. The pulsed beam enters the

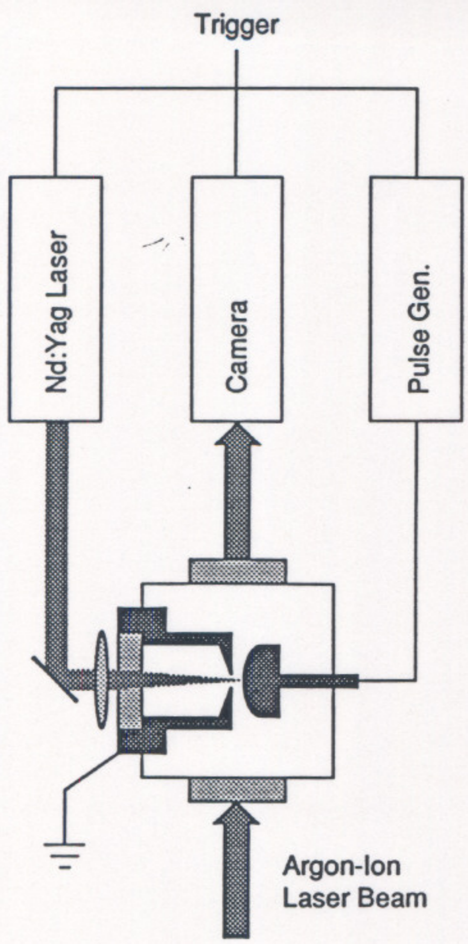

Figure 1. Schematic representation of the test gap. A pulsed laser beam enters the cell from behind the grounded electrode and is brought to a focus at the surface of the high-voltage electrode. The gap is photographed by a high-speed framing camera.

cell through a window mounted behind the grounded electrode and is brought to a focus at the surface of the high-voltage electrode. The portion of the incident light absorbed upon reflection from the electrode surface is sufficient to vaporize the liquid at the surface and to produce an acoustic pulse that propagates from the point of laser impact. The Nd:YAG laser light was frequency doubled to produce radiation at 532 nm; and the pulse energies reported here were measured following the frequency doubler.

The test gap was illuminated by light from an argon-ion laser and photographed by a high-speed framing camera, which was synchronized with the pulsed laser. This configuration proved useful in identifying laser intensities below the threshold for damage to the fluid since it allowed the effects of the pulsed beam to be examined both with and without voltage applied. For pulse energies on the order of 20 mJ and above, the fluid was heavily damaged by the pulsed beam: Photographs of the gap showed damage along the path of the beam and a weak shock that propagated in a radial direction away from the beam path. A weak shock also propagated away from the point-of-impact on the electrode surface and a large bubble, expanding to approximately 2 mm in diameter, formed at the surface. For pulse energies on the order of 5 mJ, there was no apparent damage to the fluid, however, the shock emanating from the point of laser impact and the formation of a large bubble, again, expanding to approximately 2 mm in diameter, persisted. Pulse energies on the order of 0.5 mJ also showed the formation of a bubble on the electrode surface and a weak shock. For this case, however, the size of the bubble was approximately 500 μm and the shock was much less intense. The results presented below were obtained at this energy.

The test gap was charged by a voltage pulse generated by using an impulse transformer and a pulse-forming network. The total time duration of the voltage pulse is approximately 12 μs: The waveform has a 4-μs raise-time, which is followed by a voltage plateau lasting approximately 3 μs. The pulsed laser, impulse-voltage generator, camera and other diagnostics were all synchronized to a single trigger. The beam from the pulsed laser was timed to arrive near the onset of the plateau voltage, that is, approximately 4 μs after the start of the pulse voltage.

The electrodes were enclosed within an insulating cell and were immersed in the fluid. The cell was filled with ultra-pure grade hexanes, which was used as received without degassing or further purification. The liquid was, however, circulated and filtered upon filling the system and as needed throughout the course of these tests.

Results

The criteria used to establish a proof-of-principle are: 1) a spatial coincidence between the discharge site and the point of beam impact, 2) a clear temporal relationship between the discharge and the time-of-arrival of the pulsed beam, and 3) a voltage required for triggered breakdown that is less than the self-break voltage.

That two of these criteria are satisfied can be read-

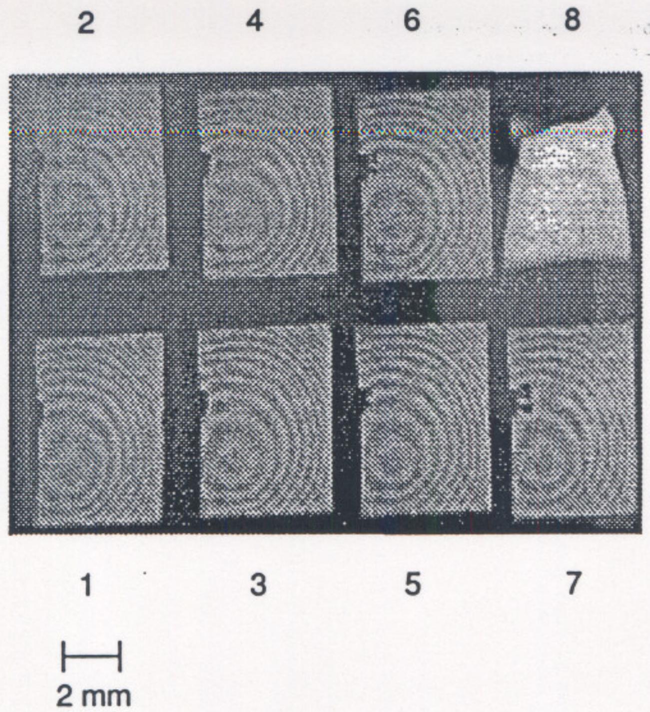

Figure 2. Frame photograph of a laser-triggered discharge. The pulsed laser beam impinges on the surface of the high-voltage electrode, which is shown on the left, producing a small bubble. The onset and propagation of instabilities in the bubble surface is noted in frames 5–7, and the closing arc develops between frames 7 and 8. The time interval between frames is 200 ns and the frame exposure is 40 ns.

ily verified by examination of the frame photograph shown in Fig. 2. These data were obtained at a laser pulse energy of 0.5 mJ and for a positive potential applied to the triggered electrode. The voltage at the time-of-arrival of the laser pulse, which, for these data, falls 3 μs before the first frame, was approximately 100 kV. The location of the small bubble appearing in the first frame corresponds to the point-of-impact of the laser beam. The experimental conditions for these data were identified by fixing the pulse energy and increasing the magnitude of the impulse voltage in a stepwise fashion until a triggered discharge was observed. There appeared, by this method, to be a distinct threshold voltage for the onset of instabilities in the bubble surface. The surface of the bubble appeared to deform as voltage was applied, however, the surface remained stable for voltages just below that required to achieve triggered breakdown.

The third criterion, the relative integrity of the triggered and untriggered gaps, was examined by a later series of tests. Comparing the voltages required for 50% probability of electrical breakdown, the self-breaking and triggered gaps required voltages of 160 and 120 kV, respectively, as measured by the maximum voltage in the waveform. There would thus appear to be a significant reduction in the voltage required for the laser triggered discharge described here.

Discussion

The dynamical behavior of the triggered discharge shown in the figure appears to be much the same as that noted for prebreakdown streamers in self-breaking gaps. The negative streamer has probably been characterized most extensively; an overview of this topic has been given recently by Hebner [6]. In a self-breaking gap, the streamer initially propagates at speeds much less than the sonic velocity and undergoes an abrupt transition to a faster streamer that bridges the gap. The closing arc forms along a path defined by the streamer. Although not reported as widely, the same qualitative behavior has been noted for positive streamers [7], which is the case presented here. The triggered discharge proceeds first through a subsonic phase: by the onset and propagation of instabilities in the bubble surface. Surface instabilities are noted in the figure by the finger-like projections in the bubble surface. The rate of propagation of these projections is on the order of 30% of the sonic velocity. The closing arc develops between frames 7 and 8 and is clearly attached to the point of laser impact.

It should be noted that the criteria given above were not satisfied for more energetic laser pulses: the breakdown voltages for the self-breaking and triggered gaps were practically the same, the location of the discharge and the damage produced by the laser did not appear to be correlated, and the onset for surface instabilities in the bubble formed by the laser was not observed. These observations may appear to be counter intuitive, since it would seem that the integrity of the gap would be more severely compromised by the extensive damage produced at higher energies and that breakdown would thus occur more readily. However, we believe these observations may be reconciled by the proposed mechanism: The behavior noted at low pulse energies appears to agree in several key aspects with model predictions for the dynamical behavior of a charged surface [8]: the product of local field strength and charge density must exceed a threshold value for the onset and propagation of a surface instability; and that the triggered streamer appears to display a characteristic size and rate-of-propagation. We then presume that free charge of the same polarity as the applied potential is transferred to the fluid during the pulse charge. The pulsed laser, once fired, separates the fluid from the electrode thus creating a surface that is free to evolve under the influence of the local charge and electric field. The apparent anomalous behavior noted above for higher pulse energies may thus be consistent with a reduction in the charge density at the fluid boundary: The local charge density may be reduced by the rapid expansion of the bubble, which, in effect, may stabilize the surface.

The pulsed laser system used for these studies was designed to operate at much higher energies than the 0.5 mJ reported here. This energy was chosen, in part, as a compromise value in order to obtain reasonable shot-to-shot reproducibility. If the scenario presented above is valid, the size of the bubble needed to launch the discharge would be comparable to that of the prebreakdown streamer. It may thus be possible to trigger a discharge by creating a micro-bubble sized on the order of tens of microns. The minimum power required to trigger a discharge by this method may be much less than the 0.5 mJ reported here.

Conclusions

The results presented demonstrate that an electrical discharge can be triggered in a fluid filled gap by a pulsed laser system at pulse energies much lower than reported previously. The discharge is initiated by directing the laser beam onto the surface of one electrode to produce a bubble on the surface. The observed mode of breakdown appears to be consistent with that noted in self-breaking gaps.

Acknowledgements

This work was conducted in the Electricity Division, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Technology Administration of the U.S. Department of Commerce. Partial support for this work was also provided by FAPESP-BRASIL.

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95CH35842

1995 Annual Report

Conference on Electrical Insulation and Dielectric Phenomena

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95CH35842

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1995 Annual Report

Conference on Electrical Insulation and Dielectric Phenomena

October 22 - 25, 1995

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And Conference Center
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