

WATER AND PROPYLENE CARBONATE AS STORAGE AND SWITCHING MEDIA IN PULSED POWER SYSTEMS *

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The electrical characteristics of two polar liquids, water and propylene carbonate, under high electric stress has been studied. The liquids were placed between a hemispherical electrode of 1.7 mm diameter and a plane electrode with gap distances of 200 μm and 400 μm , respectively. A voltage pulse of 200 ns duration was applied by means of a Blumlein pulse generator. The increase in current with voltage was recorded up to the breakdown voltage, including the transition phase to breakdown. Schlieren diagnostics, with a temporal resolution of 2 ns, was used to study the changes in the index of refraction of water as switch medium, before and during breakdown. The results of our measurements showed that the electrodes determine, to a large extent, the hold-off voltage. By polishing the stainless steel electrodes, the breakdown strength was increased from 1 MV/cm to 2.2 MV/cm for propylene carbonate as dielectric. Similar increases were found for water as dielectric between polished electrodes. The rate of current rise after breakdown was measured as $4.5 \cdot 10^{11}$ A/s for distilled water, a value which is comparable to that measured in gas switches. The Schlieren photographs showed that depending on the polarity, the breakdown is preceded by the treeing of streamers into the gap.

I. INTRODUCTION

The high relative dielectric constant of the two polar liquids studied, 80 for water, 66 for propylene carbonate, allows for a compact, high energy density storage system. The high dielectric strength, which was previously measured as 1 MV/cm [1], enables one to build small low inductance switches. The disadvantage of using polar liquids, however, is their relatively high conductivity, which requires pulsed charging if used as dielectric in pulsed power systems.

With respect to pulsed power applications, we have measured the resistive losses of propylene carbonate and water in a submillimeter gap for high, pulsed electric fields. Secondly, we have measured the dielectric strength of these liquids depending on conductivity of the liquid, and on electrode surface structure. A crucial parameter for switching the current rate of rise after breakdown was measured using distilled or tap water as the switching medium. In addition, the initiation of breakdown was studied using Schlieren photography.

II. EXPERIMENTAL SETUP AND PROCEDURES

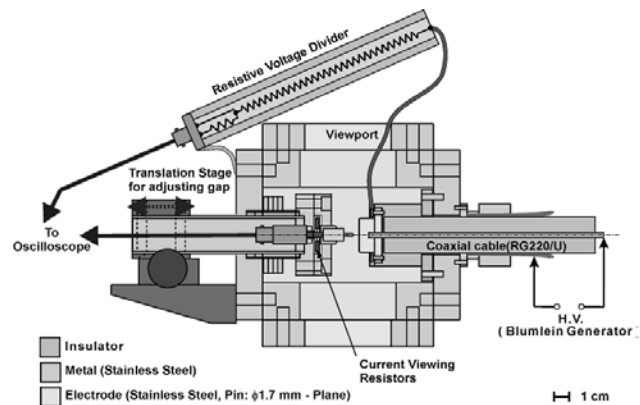


Figure 1. Schematic drawing of the discharge chamber and electrical probes.

In the discharge chamber shown in Fig. 1, a pin electrode with a hemispherical tip of 1.7 mm diameter is facing a plane electrode of 20 mm in diameter. Both electrodes are made of stainless steel. The gap distance can be varied from zero to 1 mm with an accuracy of 5 μm . For most of the electrical experiments described in

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this paper, the gap distance was set to 200 μm ; for the Schlieren photography it was set to 400 μm . The surface of both electrodes was either ground with sandpaper of grain 400 or polished in several steps, eventually using a 6 μm diamond paste. With a light microscope it was verified that the size of remaining asperities is smaller than 10 μm . After additional polishing with a 1 μm diamond paste, one set of electrodes was coated in a sputtering system with a copper layer of approximately 3 μm thickness.

For the measurements, the electrodes were completely immersed in tap or distilled water and propylene carbonate, respectively. The tap water used for the experiments had a resistivity of 7 $\text{k}\Omega\text{cm}$, the resistivity of distilled water was 400 $\text{k}\Omega\text{cm}$. In order to de-gas the water it was kept for two days at room temperature in a 2-liter dessicator in a low pressure atmosphere of 10 mbar. Propylene carbonate with a purity grade of almost 100% was received from Sandia National Laboratories. Its resistivity was measured as approximately 200 $\text{k}\Omega\text{cm}$.

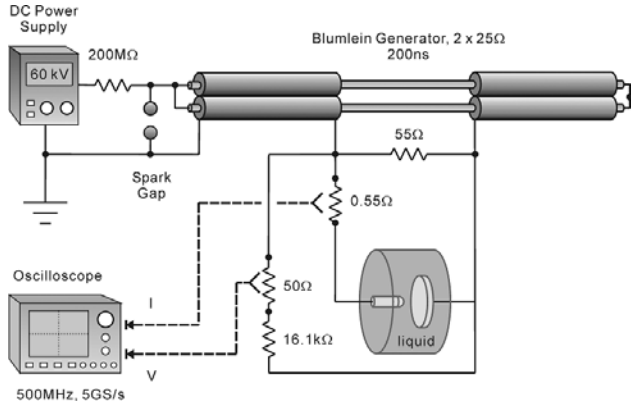


Figure 2. Electrical circuit (including diagnostic circuits)

The electrical setup of the system is shown in Fig. 2. The pin electrode is connected to ground through a current viewing resistor of 0.55 Ω . Superimposed with the resistive current is a capacitive component, $C \cdot dV/dt$ (C : capacitance, dV/dt : rate of voltage rise). C is determined by the gap capacitance and the capacitance of the high voltage electrode to the surrounding full metal experimental chamber. The ratio of the displacement current to the resistive current depends on the ratio of conductivity σ and dielectric constant ϵ of the liquid. For the rather low conductivity of propylene carbonate and distilled water, the amplitude of the displacement current for a 200 ns long voltage pulse is much larger than the resistive current, which provides information on the liquid, rather than the electrode and chamber geometry.

The electrode polarity can be changed. However, with one exception the voltage applied to the plane electrode (pin electrode was always on ground potential) was negative, leaving the pin electrode to be the anode. The voltage drop across the gap was measured with a resistive voltage divider (50 Ω /16.1 $\text{k}\Omega$), the current was measured

with a current viewing resistor (0.55 Ω). After each voltage pulse the liquid was partially drained and, in this way, replaced between the electrodes.

With a Blumlein pulse generator, almost rectangular voltage pulses of 200 ns duration were provided to the electrodes. The Pulse Forming Network (PFN) consists of two 50 Ω coaxial cables (RG-217) in parallel, and therefore its output impedance is 50 Ω . To match the PFN, a 55 Ω resistor is placed in parallel with the water gap at the output terminal of the pulse generator. The Blumlein line is charged through a 200 $\text{M}\Omega$ resistor up to voltages of 45 kV using a DC high voltage power supply (Glassman High Voltage). The pulse is generated and applied by manually closing a spark gap between the high voltage conductor and the grounded conductor of the cables.

Two glass windows are placed on opposite sides of the experimental chamber to allow optical access to the electrode area. With a Schlieren system using a 10 mW He-Ne laser and a fast gated ICCD camera (4Picos, Stanford Computer Researchers), optical phenomena during application of the voltage pulse, breakdown and post breakdown phase [2] can be recorded. The camera shutter time was 2 ns.

III. RESULTS AND DISCUSSION

A. Simulation of Electric Field Distribution and Resistive Losses

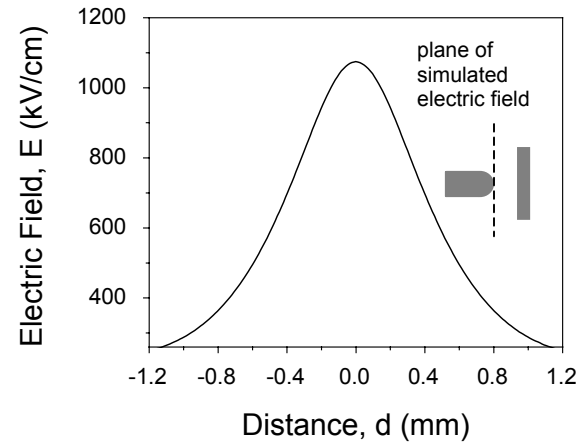


Figure 3. Simulated electric field distribution in radial direction for a voltage drop of 20 kV across the electrodes and a gap distance of 200 μm in the plane through the tip of the pin electrode.

The distribution of the electric field between the electrodes was simulated using the simulation software package Estat (www.tricom.com). The field distribution at the pin electrode is shown in Fig. 3 for an applied voltage of 20 kV; field strength is maximum at the tip of the pin electrode. The simulated maximum electric field is in good agreement with that obtained from the semi-empirical Eq. (1) [3].

$$E_{\max} = 0.9 \cdot \frac{V}{a} \cdot \frac{r+a}{r} \quad (1)$$

Here, r stands for the radius of the hemispherical electrode, a for the gap distance and V for the applied voltage. For a gap distance of $200 \mu\text{m}$ the electric field strength is decreasing by almost one order of magnitude within 1 mm distance in radial direction from the gap axis. However, in the axial direction, at the plane electrode, the electric field is only 15% less than the maximum value at the tip. From the field distribution $E(\vec{r})$ the current I flowing across the gap for the given conductivity σ of the dielectric between the electrodes can be calculated from Ohms law:

$$I = \int_0^{d_0/2} \sigma \cdot E(\vec{r}) 2\pi r dr \quad (2)$$

Neglecting the variation of the electric field in axial direction towards the plane electrode, the comparison with the experimental results showed a good agreement with the calculation, for an assumed diameter, d_0 , of 10.8 mm for the cylindrical current-carrying area.

B. Current-Voltage Characteristics Below Breakdown Threshold

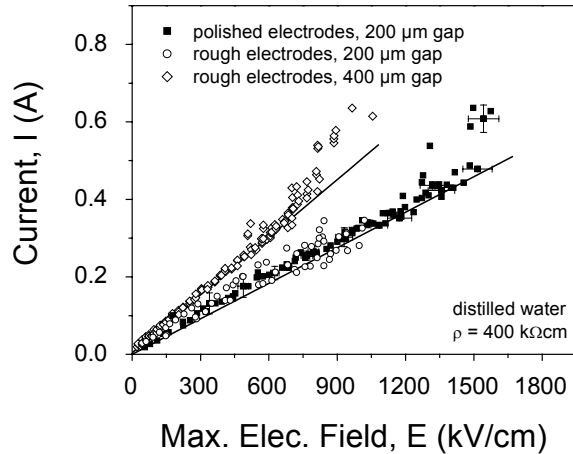


Figure 4. Current-voltage characteristics for distilled water up to the critical electric field for breakdown for different surface textures and electrode distances.

Current-voltage characteristics for distilled water between polished and unpolished electrodes are shown in Fig. 4. Up to the breakdown voltage, the resistive current through the distilled water between the electrodes is linearly increasing with voltage and is defined by the known resistivity of the distilled water. Close to the breakdown voltage the current is increasing superlinearly to values 1.5-2 times higher than expected based on the lower electric field resistivity value. This result indicates that breakdown is preceded by the formation of current pathways across the gap.

The breakdown voltage was measured as approximately 33 kV for a $400 \mu\text{m}$ gap distance and 18 kV for $200 \mu\text{m}$. According to Eq. (1), breakdown voltage corresponds to a critical electrical field strength of 1 to 1.1 MV/cm , independent of the gap distance for this geometry. In order to study the effect of the surface texture on the breakdown voltage, the characteristics of distilled water between polished electrodes was compared to that obtained with electrodes ground with sandpaper. For the rough electrodes, the breakdown strength was again found to be on the order of 1 MV/cm , independent of the gap distances ($200 \mu\text{m}$ and $400 \mu\text{m}$). However, for polished electrodes the breakdown voltage for a $200 \mu\text{m}$ gap was measured as 28 kV , corresponding to a breakdown field close to 1.6 MV/cm . No breakdown could be observed in a $400 \mu\text{m}$ gap up to a pulse voltage of 45 kV , the largest voltage value obtainable with our present experimental setup. After a single breakdown the hold-off voltage between the electrodes that were damaged by this discharge decreases to the breakdown field value typical for unpolished electrodes.

An even smoother electrode surface than through polishing was achieved by coating the electrodes with copper. However, the breakdown strength was 800 kV/cm lower than that for unpolished stainless steel electrodes. Furthermore, the resistive current between the electrodes is almost twice as high as for uncoated stainless steel electrodes but still increased linearly with voltage. The higher current might be due to copper ions that are dissolved in the water and are contributing to the conductivity.

To investigate the effect of dissolved gas in the dielectric liquid on the breakdown threshold, we studied the electrical characteristics of de-gassed distilled water. No significant difference, either in breakdown voltage or in the current-voltage characteristic, was found when compared to distilled water. The current-voltage characteristic was also found to be linear. The breakdown strength is, as in the case of not-treated distilled water, dependent on the polarity. It is less (1.3 MV/cm) if the hemispherical electrode is the cathode, rather than the anode (1.5 MV/cm). Surprisingly, the dielectric strength of tap water was found to be 2 MV/cm , 33% higher than for distilled water. However, because of its higher conductivity, the leakage current is much higher (Fig. 5) than for distilled water.

The highest breakdown strength of 2.2 MV/cm could be obtained with propylene carbonate as dielectric between polished electrodes. This current voltage characteristic differs from that of water as shown in Fig. 5. Up to approximately 1.5 MV/cm , the current linearly increases with voltage and can be described by the resistivity of this dielectric. Beyond 1.5 MV/cm the slope of the current-voltage characteristic changes. The current still increases linearly with voltage, but the slope indicates an increased conductance.

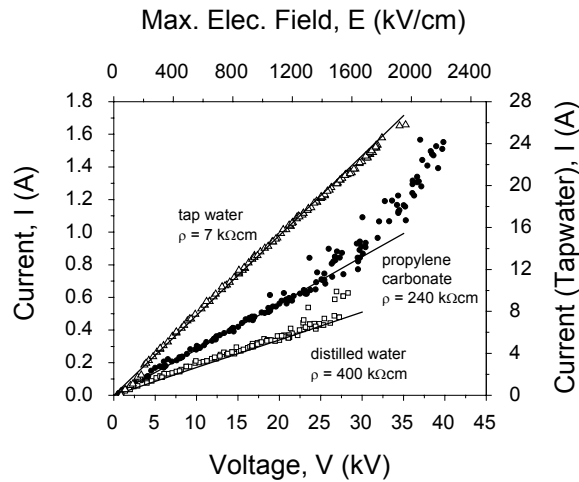


Figure 5. Current-voltage characteristics of tap water, distilled water, and propylene carbonate for polished electrodes and positive polarity.

In all experiments, the breakdown voltage decreases after a single breakdown to the value typical of unpolished electrodes.

C. Breakdown Studies

For unpolished electrodes and a gap distance of 400 μm , the rate of current rise after breakdown in distilled and tap water, respectively, was measured. With a maximum value of $4 \cdot 10^{11}$ A/s the rate is almost twice as high for distilled water as for tap water ($2.5 \cdot 10^{11}$ A/s). These values are comparable to, or even exceed, rates of current rise for gas switches, such as thyratrons [4].

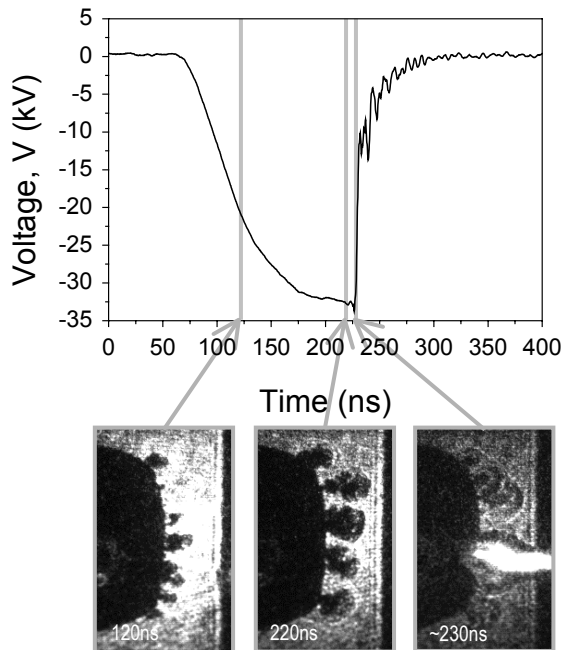


Figure 6. Streamer development (pin electrode: cathode).

The transition into breakdown was studied by means of Schlieren photography. Only if the hemispherical

electrode is cathode, are streamers observed that grow with a propagation velocity of 10^5 cm/s into the gap while a voltage is applied. Eventually, a plasma channel develops out of one of these trees, and causes breakdown. However, if the voltage decreases to zero before gap closing, these trees shrink until they finally vanish again at the cathode.

IV. SUMMARY

The experimental results with electrodes of differing surface quality indicate the importance of the boundary layer between electrodes and liquid dielectrics under high electric stress. The boundary layer seems to be even more important for maximum dielectric strength than the properties of the polar liquid. The polishing of the stainless steel electrodes has allowed us to increase the dielectric strength of propylene carbonate and tap water by more than a factor of two, and for distilled water by a factor of 1.5, over values that were so far considered the maximum. For propylene carbonate, at a dielectric strength of 2.2 MV/cm, the possible maximum storable electric energy density is 14 J/cm^3 , the same as for tap water, which has a dielectric strength of 2 MV/cm. These high values of energy density allow the construction of very compact intermediate energy storage systems for pulsed power applications. The still high breakdown field for unpolished electrodes, 1 MV/cm for both water and propylene carbonate, allows their use in micro switches with current rates of rise comparable to and better than that of gas switches. Finally, the possibility of exchanging the liquid in such micro switches on time scales of less than ms [5], adds the additional advantage of high repetition rate operation to these high power liquid dielectric switches.

V. REFERENCES

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