CHINESE JOURNAL OF CHEMICAL PHYSICS VOLUME 28, NUMBER 5 OCTOBER 27, 2015

ARTICLE

Polarity Effects of Propylene Carbonate on Breakdown Strength in Microsecond Range

Zhen Wang, Zi-cheng Zhang*, Jian-de Zhang

College of Opto-electronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

(Dated: Received on April 22, 2015; Accepted on May 13, 2015)

We investigate the polarity effects of the propylene carbonate on the breakdown voltage using the needle-plate electrodes with gaps of 0.5, 1.0, and 2.0 mm. The devices used in this study involve a compact capacitive-energy-storage pulse power source with charging time varying from 5 ms to 20 ms and a test cell with the needle-plate electrodes. The breakdown voltage is recorded by a digital oscilloscope for each gap. The results of these three groups indicate that the positive breakdown voltage is higher than the negative one and the breakdown voltage of the PC increases with the ascending electrode gap. In addition, a simulation is conducted to support this experiment. Some explanations about the polarity effect of the PC are also given.

Key words: Breakdown strength, Propylene carbonate, Polarity effect

I. INTRODUCTION

Development of high power microwave (HPM) technology requires high power pulse conditioning system with high output power, compact structure and small volume [1, 2]. Pulse forming line (PFL) as the energy storage device occupies up to above 60% volume in the capacitive-energy-storage pulse power system. In this case, reducing the volume of PFL will benefit the compactness and miniaturization of the pulse power system. To achieve this goal, improvement of the energy density of the storage medium in PFL is significant in this research area. Liquid dielectric has been widely used as the energy storage medium in PFL due to its high density, good self-healing, and easy-shaping [3, 4]. The ideal storage liquid dielectric should meet the requirements of high permittivity, high breakdown strength and high resistivity [5], whereas presently liquids used as the energy storage medium in engineering applications can not completely satisfy. For example, deionized water has high energy density for its great dielectric constant (about 80) and high breakdown strength. However, water can absorb the gas from the air and split it into hydrogen and oxygen, which make it difficult to maintain the resistivity of water in a high level.

As a new high-energy-storage-density liquid dielectric, the breakdown strength and the dielectric constant of the propylene carbonate (PC) can reach 2 MV/cm and 65 respectively [6]. Furthermore, the resistivity of the PC can increase to 20 TΩ·cm through purification of the electro-dialysis system [7] and its resistivity can keep a high level in a well-closed container. Therefore, PC is a promising substitute for water as the energy storage medium in the high power pulse conditioning system [5]. In addition, the polarity of liquids has a great impact on the structure of the PFL. For instance, negative breakdown strength of water is twice as much as the positive one in the PFL [8]. However, precise data on polarity of the PC are scarce. We will discuss the polarity effects on the breakdown voltage of the PC by using the needle-plate electrodes with gaps of 0.5, 1.0, and 2.0 mm.

II. TEST PLATFORM

The circuit diagram of the testing system is shown in Fig.1. The system is initially supplied by city power with a frequency of 50 Hz. After half-wave rectification, it becomes the direct current and charges the primary capacitor. Once the main thyristor is triggered by a computer, pulse forming line would be charged through the Tesla transformer. The test cell connected to the pulse forming line in parallel is also charged. When the voltage of the test cell reaches the threshold value of the liquid dielectric, breakdown will occur. At the same time, the voltage waveform of the whole breakdown process is captured by the oscilloscope. By adjusting the voltage from 150 V to 600 V applied on the primary capacitor, we can get the corresponding high voltage from 30 kV to 120 kV in the test cell [2]. Picture of the test cell is shown in Fig.2. The cell is a 20 cm×20 cm×20 cm stainless steel box with the needle-plate electrodes made from brass.

---

*Author to whom correspondence should be addressed. E-mail: successchang@163.com

DOI:10.1063/1674-0068/28/cjcp1504080

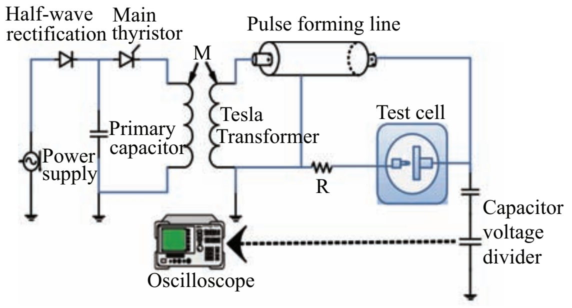

FIG. 1 Schematic diagram of the testing platform.

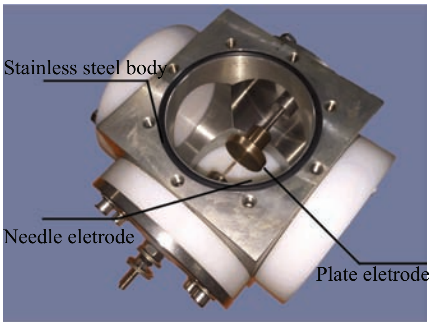

FIG. 2 Photograph of breakdown test cell.

III. SIMULATION OF ELECTRIC DISTRIBUTION

To simulate the electric distribution of the test cell, a 3-D model of the needle-plate electrodes is constructed in Ansoft Maxwell software. Two measuring lines are drawn separately from the center to the edge along the plate electrode surface and covering the needle electrode surface (Fig.3). The measuring lines are used to display the electric field strength so that the effective area of the plate electrode can be computed. The effective area is defined as the area suffering over 90% of the maximum electric field intensity. Based on the numerical analysis, the electric potential distribution around the needle-plate electrodes (Fig.3), the electric field degree from the center to the edge along the plate electrode surface (Fig.4(a)) and the electric field degree covering the needle electrode surface (Fig.4(b)) are obtained. Obviously, the highest degree of electric field appears in the surrounding area of the needle electrode, which is also the main breakdown area in the needle-plate electrodes. By finding out the corresponding points (Fig.4), A_+ and A_- which are the effective areas of the plate electrode and the needle electrode can be acquired after simple calculation. Here, A_+=0.985 mm^2 and A_-=0.993 mm^2, namely, they approximately equal to each other.

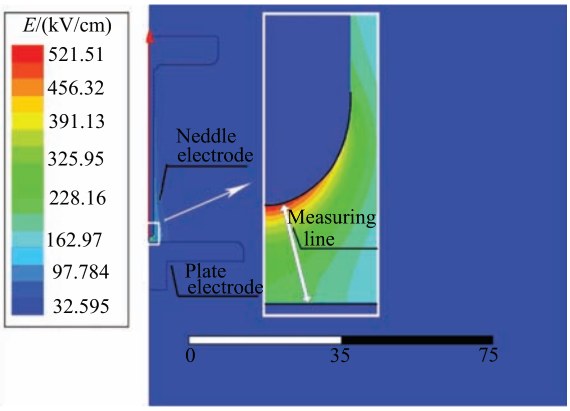

FIG. 3 Distribution image of electric potential around the electrodes.

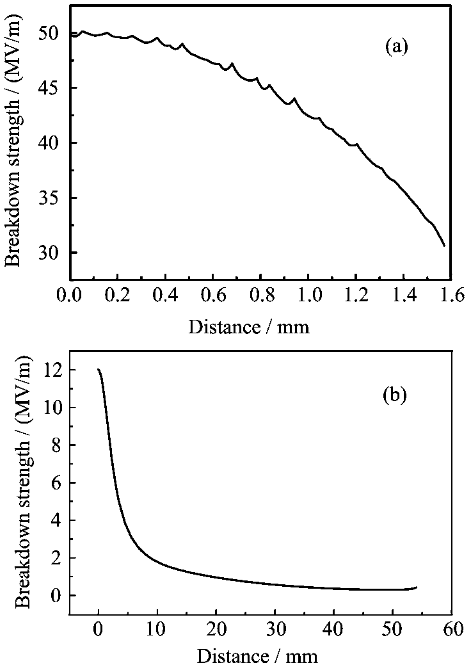

FIG. 4 (a) Plate electrode electric field changes and (b) Needle electrode electric field changes along the measuring line.

IV. EXPERIMENTAL RESULTS

Weibull distribution is adopted in the data analysis of breakdown voltages of liquids as it can limit random jitter [9, 10]. Eq.(1) illustrates the breakdown probability of the PC under high voltage circumstance.

$$F(E_t)=1-\exp\left[-\left(\frac{E_t}{\beta}\right)^{\alpha}\right] \tag{1}$$

where E_t is normalized breakdown field strength, $F(E_t)$ is breakdown probability, α is the shape parameter related to scatter of the data, β is the dimension parameter. For example, $E_{0.5}$ is the normalized breakdown

DOI:10.1063/1674-0068/28/cjcp1504080

TABLE I Polarity effects on breakdown strength of PC.

Electrode polarity	Electrode gap/mm	β	α	50%U_{bd}/kV	95% confidence interval/kV	S_d[a]/kV
Needle negative	0.5	44.5	6.7	42.1	(38.5, 45.8)	6.4
	1.0	54.8	8.4	52.5	(49.1, 55.8)	7.7
	2.0	95.3	9.3	91.6	(85.7, 97.5)	12.2
Needle positive	0.5	60.7	7.8	57.9	(54.0, 61.8)	8.5
	1.0	76.8	9.0	73.7	(69.3, 78.1)	9.7
	2.0	109.3	8.0	104.4	(97.1, 111.7)	14.7

[a] S_d is standard deviation.

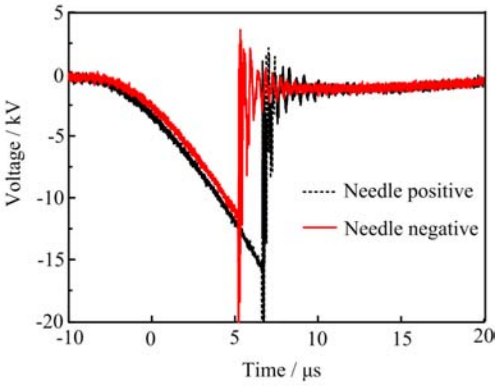

FIG. 5 Breakdown voltage comparison between needle positive and needle negative at the gap of 0.5 mm.

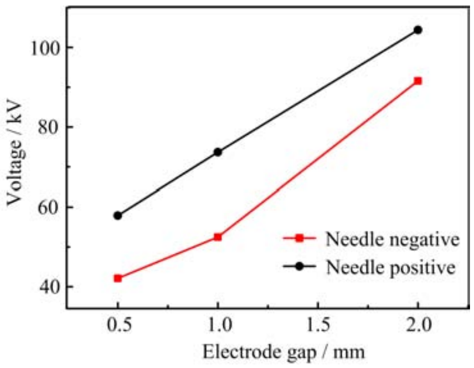

FIG. 6 Effect of electrode gap on the polarity of PC.

field strength with a breakdown probability of 0.5 and it represents the breakdown strength in this work. When Eq.(1) equals to 0.5, Eq.(2) can be obtained as follows [11−14]:

$$E_{0.5} = \beta(\ln 2)^{1/\alpha} \tag{2}$$

The value of $E_{0.5}$ can be calculated by importing the data collected from the experiments into a software which is developed by MATLAB. The two parameters and 95% of their confidence interval can be ascertained with the command “wblfit”.

By adjusting the needle-plate electrode gap to 0.5, 1.0, and 2.0 mm, the breakdown voltages are recorded and each gap is tested 30 times. The experimental results after data analysis are listed in Table I. It is obvious that the breakdown voltage increases with the widening electrode gap. Moreover, the data demonstrated that the positive breakdown voltages are 37.5%, 40.4% and 14.0% respectively higher than the negative ones for each gap. The voltage waveforms recorded by the oscilloscope are presented in Fig.5. The results in Fig.6 also indicate that the effect of positive polarity of the PC weakens when the electrode gap rises to 2 mm.

V. ANALYSIS AND DISCUSSION

Matin *et al.* first investigated the breakdown of water dielectric and conducted many experiments under the standard temperature and pressure in 1960s [8]. Two most important formulas Eqs.(3) and (4) were discovered to describe the rules of water breakdown.

$$E_{+} = 300t_{\mathrm{eff}}^{-1/3}A^{-1/10} \tag{3}$$

$$E_{-} = 600t_{\mathrm{eff}}^{-1/3}A^{-1/10} \tag{4}$$

here E_{+} and E_{-} in kV/cm are positive and negative breakdown strength respectively, A in cm^2 is the effective electrode area which is defined as the area suffering over 90% of the maximum electric field intensity, t_{eff} in µs is the effective time which is defined as the time suffering over 63% of the maximum voltage. An obvious conclusion can be drawn from Eq.(3) and Eq.(4) that the negative breakdown strength is approximately twice as much as the positive one. The classical Martin formula is developed to Eq.(5) based on the later research from Fenneman and Gripshover [4, 15, 16].

$$E_{\mathrm{bd}} = MA^{-1/10}t_{\mathrm{eff}}^{-1/N} \tag{5}$$

where E_{bd} in kV/cm is the breakdown strength of water dielectric and M is a constant related to the properties of water and the quality of the electrode. In Ref.[4], a much different conclusion is drawn that M of the negative breakdown is only 5% higher than that of the positive one by using the hemisphere (3 cm^2)-plate (81 cm^2) electrodes. It is apparently inconsistent with the results under the uniform field conditions. Therefore, it comes

DOI:10.1063/1674-0068/28/cjcp1504080

to a conclusion that under nonuniform field conditions, M of the negative breakdown is weakened.

According to the aforementioned, the consequence of our experiments that the positive voltage is higher than the negative one is reasonable. In this case, Eq.(6) and Eq.(7) are obtained by modifying the classical Martin formula.

$$E_+ = M_+ t_{\text{eff}}^{-1/N} A_+^{-1/n} \tag{6}$$

$$E_+ = M_- t_{\text{eff}}^{-1/N} A_-^{-1/n} \tag{7}$$

where E_+ and E_- in kV/cm are positive breakdown strength and negative breakdown strength of the PC respectively, M_+ and M_- are respectively field enhancement factors of positive and negative, N and n are constants decided by properties of liquids and shape of the electrode. Here assuming the values of t_{eff} in positive and negative breakdown are equivalent. A_+ and A_- are the effective area of the positive electrode and the negative electrode respectively. Moreover, A_+ equaling to A_- has been validated. Therefore, the comparison of E_+ and E_- mostly depends on the amplitude of M_+ and M_-. Furthermore, based on the result of $E_+>E_-$, it is concluded that the breakdown always takes place in the needle electrode whether the needle electrode is positive or not. That is to say, unlike the classical Martin formula about water, the positive field enhancement factor of Eq.(6) is greater than the negative one of Eq.(7) for the PC under the mm-level electrode gap.

Some explanations about the positive voltage higher than the negative one are given as follows. As to the needle positive, a space charge cloud can be formed easily near the anode because of the ion and electron appearance and the lower migration speed of ions. Therefore, in order to form a conductor to transfer the charge from the liquid into the anode, the local field must exceed the intrinsic breakdown field.

For the needle negative, there is a different situation. In this case, the injected electrons moves from the cathode to the anode with a high migration speed. The free electrons and oxygen in the liquid will form stable negative oxygen ions on account of much lower migration speed in the weak electric field intensity. The local field needs to be higher in order to separate these ions and transfer electrons to the anode [17]. However, the electrode gap is too narrow to generate a large amount of attachments between oxygen and free electrodes when the needle is negative in our experiments. Most free electrodes move directly to the anode without combination with oxygen. As a result, the result of the positive voltage higher than the negative one is reasonable. It can also be concluded from the experimental data that the negative breakdown voltage rises faster than the positive one with an increasing gap (Fig.6). Similarly, Forster *et al.* drew an analogous conclusion that the size of the needle-plate electrode gap had a great influence on the polarity effect [17]. They also pointed out that the polarity of perfluoro-polyether reverses with the gap widening from 5 mm to 25 mm.

VI. CONCLUSION

A research about the polarity of the PC under needle-plate electrode gaps of 0.5, 1.0, and 2.0 mm is carried out. The consequence reveals that the positive breakdown voltage of the PC is higher than the negative one under the mm-order gap. In addition, when the electrode gap increases, the positive polarity of PC is weakened.

VII. ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No.51907175).

[1] Z. C. Zhang, J. D. Zhang, and J. H. Yang, Plasma Sci. Technol. **7**, 3161 (2005).

[2] Z. C. Zhang, J. D. Zhang, B. L. Qian, C. B. Liu, T. Xun, H. Zhang, and B. Liang, IEEE Trans. Plasma Sci. **42**, 241 (2014).

[3] B. F. Bolund, M. Berglund, and H. Bernhoff, J. Appl. Phys. **93**, 2895 (2003).

[4] D. B. Fenneman and R. J. Gripshover, IIEEE Trans. Plasma Sci. **8**, 209 (1980).

[5] C. W. Tsacoyeanes, R. Payne, and M. A. Levine, USA Patent: 3903460, (1975).

[6] X. Shu, J. F. Kolb, M. A. Malik, L. XinPei, M. Laroussi, R. P. Joshi, E. Schamiloglu, and K. H. Schoenbach, IEEE Trans. Plasma Sci. **34**, 1653 (2006).

[7] N. J. Felici and R. E. Tobazeon, J. Electrostat. **11**, 135 (1981).

[8] M. Kristiansen and L. Hatfield, *Lubbock*, TX: Defense Special Weapons Agency, 79409 (1998).

[9] D. Fabiani and L. Simoni, IEEE Trans. Dielectr. Electr. Insul. **12**, 11 (2005).

[10] M. P. Wilson, M. J. Given, I. V. Timoshkin, S. J. MacGregor, T. Wang, M. A. Sinclair, K. J. Thomas, and J. M. Lehr, IEEE Trans. Plasma Sci. **40**, 2449 (2012).

[11] C. Laurent, C. Chauvet, and J. Berdala, IEEE Trans. Dielectr. Electr. Insul. **1**, 160 (1994).

[12] R. A. Schlitz, K. Yoon, L. A. Fredin, Y. Ha, M. A. Ratner, T. J. Marks, and L. J. Lauhon, J. Phys. Chem. Lett. **1**, 3292 (2010).

[13] H. Goshima, N. Hayakawa, M. Hikita, H. Okubo, and K. Uchida, IEEE Trans. Dielectr. Electr. Insul. **2**, 385 (1995).

[14] L. A. Dissado, J. C. Fothergill, S. V. Wolfe, and R. M. Hill, IEEE Trans. Dielectr. Electr. Insul. **ei-19**, 227 (1984).

[15] A. R. Miller, *High Energy Density, Fifth Symposium on Engineering Problems of Fusion Research*, New Jersey, 471 (1973).

[16] P. S. Sincerny, *Proceedings of the 3rd IEEE International Pulsed Power Conference*, New Mexico, 222 (1981).

[17] E. O. Forster, H. Yamashita, and C. Mazzetti, IEEE Trans. Dielectr. Electr. Insul. **1**, 3 (1994).