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Simulations of the initiation and propagation of streamers in electrical discharges inside water at 3 mm length gap

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Abstract

This work is devoted to the modeling of streamer discharge, propagation in liquid dielectrics (water) gap using the bubble theory. This of the electrical discharge (streamer) propagating within a dielectric liquid subjected to a divergent electric field, using finite element method (in two dimensions). Solution of Laplace's equation governs the voltage and electric field distributions within the configuration, the electrode configuration a point (pin) - plane configuration, the plasma channels were followed, step to step. The results show that, the electrical discharge (streamer) indicates the breakdown voltage required for a 3mm atmospheric pressure dielectric liquid gap as 13 kV. Also, the electric potential and field distributions shown agreement with the streamer growth, according to the simulation development time.

Key words

Streamer discharge, plasma channels, dielectric discharge, pre-breakdown, discharge simulation.

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محاكاة حاسوبيه لبدء وانتشار التدفق لتفريغ كهربائي داخل الماء لطول فجوه كهربائية 3 ملم

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الخلاصة

يخصص هذا العمل باقتراح نموذج تفريغ التدفق، والانتشار في عوازل السائل (الماء) باستخدام نظرية الفقاعة. ان التفريغ الكهربائي (التدفق) داخل السوائل العازلة تخضع للمجال الكهربائي متباين باستخدام طريقة العناصر المحدده (في بعدين). فقد تم حل معادلة لابلاس عدديا لتحديد توزيعات الجهد والمجال الكهربائي في منطقة الحل بين القطبين (الاقطاب الكهربائي على شكل نقطه (ابره) - مستوي) تكوين قنوات البلازمية في الماء في كل خطوه. تبين النتائج، ان فولتية الانهيار المطلوبة لعبور التدفق لفجوه مملوه بالماء بطوله 3 ملم بالضغط الجوي كانت 13 كيلوفولت. ايضا تتفق محاكاة توزيع الجهد والمجال الكهربائية مع نمو التدفق وزمن تطور التدفق.

Introduction

The breakdown of insulating liquids is not simple to explain and the mechanism responsible for the initiation of breakdown is still open to controversy. Many breakdown theories have been put forward since the start of research on this subject. Experimental data on the electric breakdown of liquids that were accumulated, confirm that there are several different breakdown mechanisms that cannot be described in the context of a unified theory [1-4].

There are several reasons for lack of a single theory. The complex nature of liquids makes the theoretical analysis more difficult than with glasses. Liquid quality is a critical issue. It is very difficult to create a pure liquid compared to a pure gas. It is generally accepted that liquid purity plays a very important role in the development of final breakdown [1].

In the 1920 's [5], the theory that a cavitation or the bubble process may cause a breakdown in dielectric liquid was proposed. Krasucki [6]. With the development of high speed imaging techniques, the streamer (bubble) theory was put forward to explain the breakdown processes in insulating liquids. Kao [7] derived a mathematical model of the breakdown mechanism based on the formation of gas bubbles in liquids. He assumed that bubbles might be formed in a liquid for the reasons such as, the gas which accumulates in microscopic cavities and hollows on the electrode surface. From the liquid itself by local evaporation on the surface of the electrodes due to the action of electrical current, dissociation of molecules through collisions with electrons or impurities. Due to electrostatic forces overcoming the surface tension. The electrostatic force effect causes elongation of the bubble in the electric field.

The streamer mechanism in liquids occurs if the electric field is strong enough, it is assumed that electron avalanches can initiate in the liquid [8]. Chadband and Wright [9] suggested that the cavity region (the bubble) might be ionized plasma. Cherney and Cross [10] concluded from their experiments that with a solid-liquid interface breakdown was caused by relatively slower bubble growth by a gaseous cavitation process, rather than by very fast vaporous cavitation.

This paper is aimed at the modeling of the streamers propagating within a dielectric liquid (water) submitted to a divergent electric field (point-plane electrode configuration). The aim is to determine the initiation propagation and branching of streamers in the liquid gap (water).

Principles of the model

Many theories have been put the initiation the growth of a streamer in dielectric liquid [7, 11-14]. Confirm that there are several different breakdown mechanisms that cannot be described in the context of a unified theory [2, 15].

This model, here, was built based on several assumptions to initiating the growth of a streamer within the buffer liquid. Many conditions have suggested to the start and growth of the streamer. Following are the basic assumptions of the proposed model:

1- The simulation was implemented in the two dimensional region of finite elements. Some nodes of some elements represent the electrodes, while the others represent the dielectric liquid between the electrodes.

2- The electric potential at all nodes of all elements that belongs to the dielectric is calculated by solving the Laplace equation with the boundary conditions on the electrodes and the streamer discharge pattern.

3- The likelihood of initiation and growth of a streamer can be satisfied when

i- The local electric field (in the center of finite element) is greater that a threshold value [16]. The local electric field will be calculated according to the values of the voltage at the nodes of each element. Also, the heat of liquid evaporation (W_s) is greater than the latent heat (L) [1, 17, 18].

$$W_s = R_s I_s^2 \, \Delta\tau \qquad (1)$$

Also

$$L = \rho \, . V_{ab} \, . C_p(T) . \Delta T \qquad (2)$$

when R_s is resistance streamer, I_s is current streamer, $\Delta\tau$ time duration of jump, L is the energy to heat liquid [J], ρ is the mass density liquid (kg/m^3),

V_{ab} is the Volume of bubble [m^3], $C_p(T)$ is the heat capacity of liquid (J/kg.K) and ΔT is the temperature change (K).
ii- The electric field value (E_{tip}) at the streamer tip is greater than a threshold value [19].

$$E_{tip} = 2V_0/(r_0 \ln 4\left(d - \frac{l_s}{r_0}\right) \qquad (3)$$

where V_0 is the applied voltage, d is the gap length and l_s is the length of the streamer channel and r_0 is the radius of the streamer channel.
iii- The electric field of the bubble (E_b) is greater than a threshold value [20].

$$\vec{E}_b = \frac{3\varepsilon_r}{2\varepsilon_r + 1}\vec{E}_{loc.} \qquad (4)$$

when $E_{loc.}$ is the local electric field and ε_r is the relative permittivity of the dielectric.
iv- All the streamer branches were followed for one step only, because they, at all conditions, will decay. And only the main will bridge the gap between electrodes.

Simulation and results

To validate our model, consider a pin-plane electrode geometry, submerged in an insulating (water) of relative permittivity 78.6 and submitted to different applied voltages, the radius of streamer channel r_0=5 μm and the conductivity of channel = 0.1 $(\Omega.m)^{-1}$. The model to be implemented, a computer simulation must be executed within a pin-plane electrode arrangement, Fig. 1. The pin (anode) is of 10 mm length. The plane (cathode) is about 13 mm diameter, and the distance between the electrodes is the liquid gap length of 3 mm. A positive DC high voltage was applied to the pin (V_0= 13, 15, 18, 20 and 23 kV) while the plane was grounded.
Laplace's equation governs the voltage and electric field distributions within the arrangement. So, finite element method (in two dimensions) was used as a good tool to solve Laplace's equation in the complicated arrangement (the solution region as in Fig. 2). The program was written with Fortran 77 language. It was used to do the calculations that are needed to predict the voltage and electric field distributions within the water gap between the electrodes. As well as and to simulate the path and branching of the streamer within the simulation area.

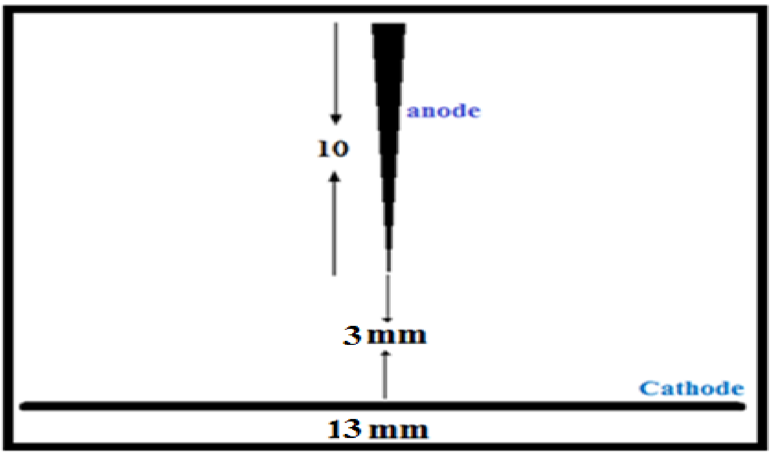

Fig.1: Longitudinal cross section of pin - plane configuration.

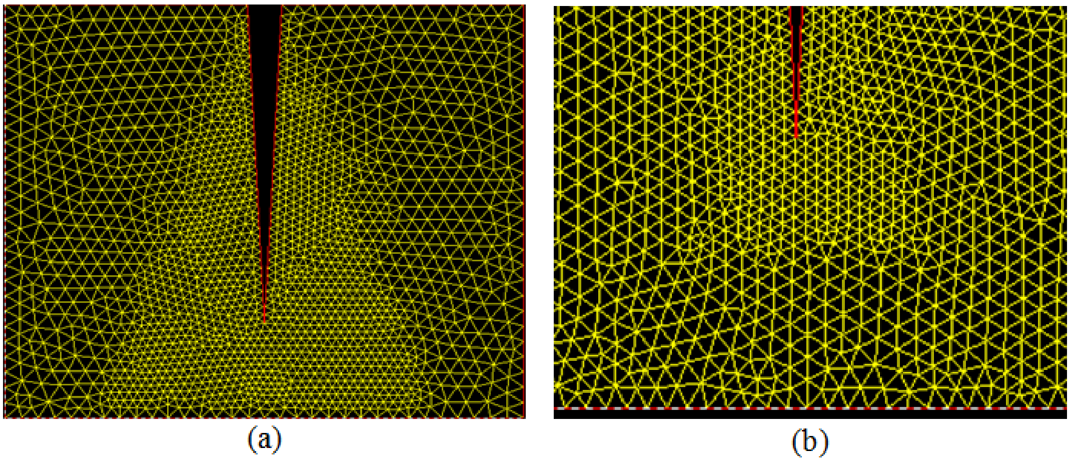

Fig.2: The grid for the pin - plane arrangement, a) a complete grid for the longitudinal cross section of the configuration, b) enlargement of the region around the tip of the pin electrode.

The Results

The simulation was carried out within the electrode arrangement of a water gap of 5 mm length to show the initiation and growth of the streamer from the anode (pin) to the cathode (plane). The aim is to determine the breakdown voltage of the water gap, show the streamer branching and the effect applied voltage V_0 on the branching streamer and the time ($\Delta\tau_{arr}$) required to arrive the plain pole.

1. The streamer development between the electrodes

The streamer initiation and development was followed within the solution region between the two electrodes. A streamer is initiated at the elements that have values that consensus with the conditions; First, the local electric field is greater than the threshold value (7.4 kV/mm) [21], and the energy injected by the electric field is sufficient to cause the evaporation of the liquid, then form the bubble [1, 15]. Second, the electric field inside the bubble is greater than the threshold (10 kV/mm) [16], the last condition; the electric field at the head of the streamer greater than the threshold (200 kV/mm) [5, 22].

The breakdown voltage gap was expecting at the minimum applied voltage value that grows streamer pattern to the gap channel. The value of the water gap of 3mm in this work was achieved at 13 kV.

Fig. 3 shows the streamer initiation and development between the two electrodes for the minimum breakdown voltage. The figure shows the initiation of the streamer at the head of the pin because of the highest values of the electric field. It is found that the initiation time is 1.71 µs and the required time for the streamer growth to embankment the gap between the two electrodes and reach the plane is 4.04 µs. Also, the streamer follows a path further away from the center of the opposite pole.

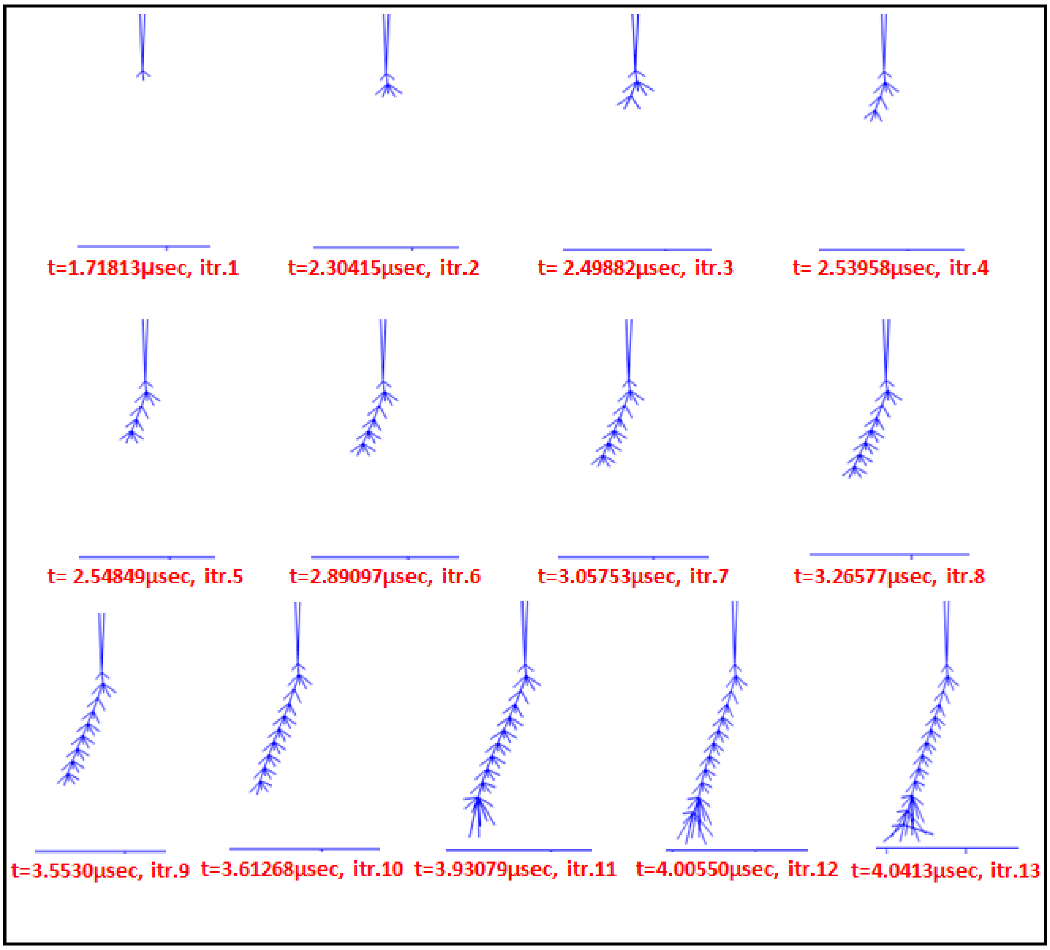

Fig. 3: The streamer development with the time within pin - plane arrangement in applied voltage of V = 13 kV.

2. Electric potential and field distributions

At first, it must know the voltage distribution as well as the field distribution, after the solution of Laplace's equation gives the voltage at every node on the mesh.

Fig. 4 and 5 show the simulation pictures of the voltage and electric field distributions development with time. It determined to support the growth of the streamer and traced the path according to voltage and electric field distribution development.

These figures indicate clearly the movement of the region of the highest voltages and the highest electric field according to the streamer growth. The plots for the magnitude of the electric field can identify the weak region where the breakdown may begin. In this case, the weak region was identified to be the region where the magnitude of the electric field is the highest, and from this region the breakdown will initiate.

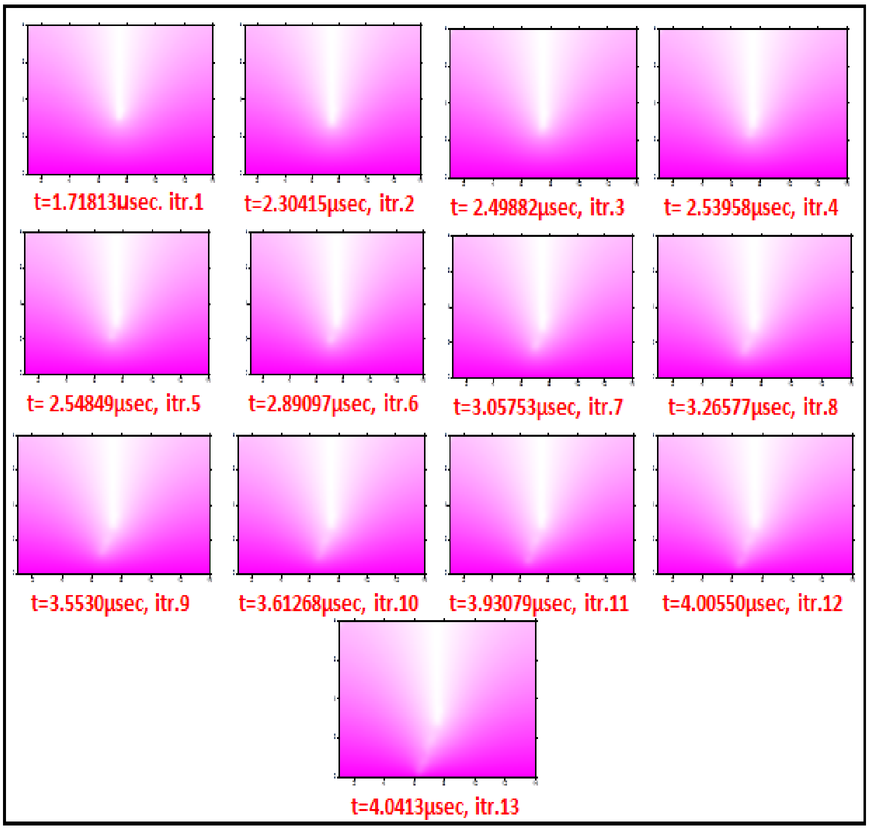

Fig. 4: The voltage distribution with the time within pin - plane configuration applied voltage of V = 13 kV.

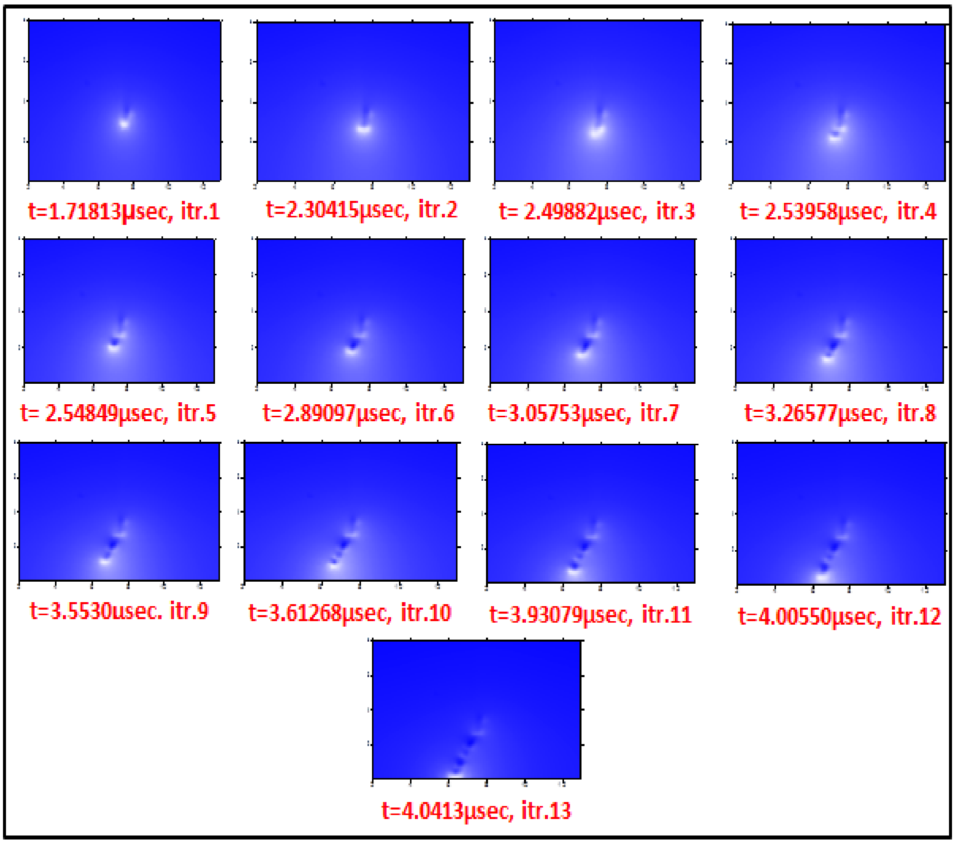

Fig. 5: Magnitude distribution to the electric field distribution with the time within pin - plane configuration in applied voltage of V = 13 kV.

3. Streamer branching

The simulation was reiterated at the same mesh, but with different applied voltages (13, 15, 18, 20 and 23 kV). That is to clarification the effect of applied voltage on the streamer branching as in Fig. 6.

From Fig. 6 the one can notice that, the number of branches increases with the increasing of the applied voltage due to the increased number of elements inside mesh that is realized condition of the growth of streamers inside liquid. Also, the streamer growth with the shortest distance between the electrodes with the increase of the voltages on the anode (pin), which leads to a decrease ($\Delta\tau_{arr}$). This is consistent with studied many experiential and theoretical researches [23, 24]. Table 1, shows the number of branches and arriving time at each applied voltage.

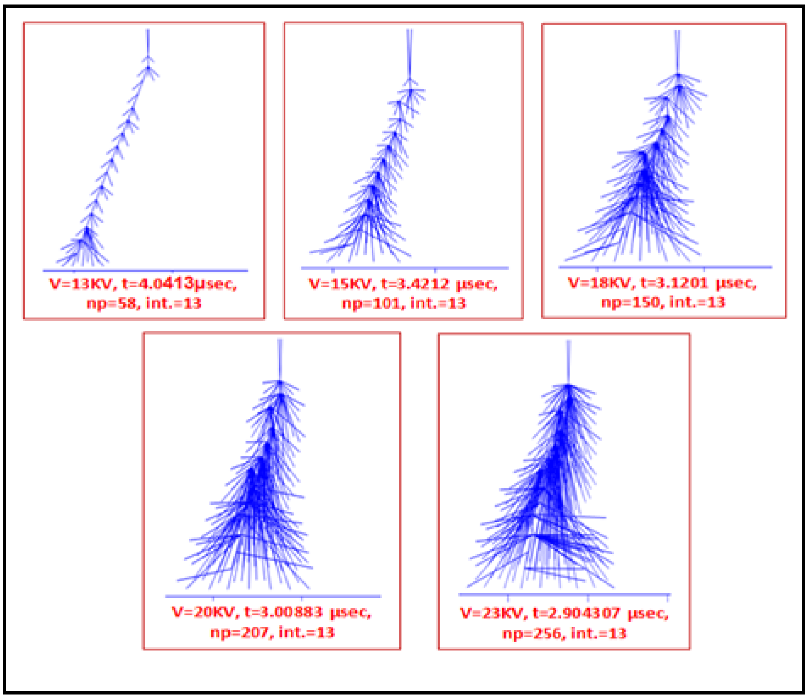

Fig. 6: The propagation and branched structures of streamers (at each time step) for different applied voltage within pin - plane arrangement.

Table 1: The arriving time and the number of branches at each applied voltage.

	Applied voltage (kV)	**Arriving time ($\Delta\tau_{arr}$) (μs)**	**No. of branches**
Dielectric liquid (Water)	13	4.04	58
	15	3.42	101
	18	3.12	150
	20	3.00	207
	23	2.90	256

Conclusions

From the results that were obtained by the simulation, the following conclusions can be presented as below:

1- The use of the computer, based on bubble model, can give good results when compared with the experimental procedures without expensive devices.

2- The higher electric field value is at the shape edge, explains the initiation of the streamer.

3- The number of branches and their positions depend on the applied voltage value.

4- The streamer velocity increases with the increasing of the applied voltage.

Acknowledgments

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References

[1] M. D. Butcher, "Mechanisms of charge conduction and breakdown in liquid dielectrics", [thesis], Texas Tech University, (2005).

[2] P. Hoffer , "Shock waves generated by corona-like discharges in water" [thesis], Czech Technical University in Prague, (2014).

[3] J. E. Master, "Photon activity from partial discharges in liquid dielectrics" [thesis], Norwegian University of Science and Technology, (2014).

[4] X. Wang, "Partial disgcharge behaviours and breakdown mechanisms of ester transformer liquid under AC stress", [thesis], University of Mancheste, the Faculty of Engineering and Physical Sciences, (2011).

[5] O. Lesaint and M. Jung, Journal of Physics D: Applied Physics, 33 (2000) 1360-1368.

[6] T.V. Top, G. Massala, O. Lesaint, IEEE Transactions on Dielectric and Electrical Insulation, 9 (2002) 76-83.

[7] K. C. Kao, Nature, London, 208 (1965) 279-238.

[8] H.M. Jones and E.E. Kunhardt, J. Phys. D.: Appl. Phys., 28 (1995) 178-188.

[9] R. Kattan, A. Denat, O. Lesaint, J. Appl. Phys., 66, 9 Nov. (1989) 4062-4066.

[10] E. A. Cherney and J. D. Cross, IEEE Trans. Electr. Insul., EI-12, 3 June (1977) 214-218.

[11] A. H. Sharbaugh and P. K. Watson, "Conduction and breakdown in liquid dielectric," Progress in Dielectric, J. B. Briks and J.Hart, Eds., Academic Press Inc., Publishers, New York, Vol. 4, (1962).

[12] K. C. Kao, IEEE Trans. Electr. Insul., EI-11, 4 Dec. (1976) 121-128.

[13] Z. Krasucki, Proc. Royal Soc. Series. A., 294 (1966) 393-404.

[14] W. R. Thomas, Ann. Rep. Conf. on Electr. Insul. and Dielectric Phenomena, National Academy of Sciences, Washington D. C., (1973) 130-163.

[15] Au-Dung Vuong, "Energy Considerations of Initiation of Fast Streamers in Cyclohexane" [theses], Norwegian University of Science and Technology, 2015.

[16] T.J. Lewis, IEEE Trans. on Dielectrics and Electrical Insulation, 5, 3 June (1998) 306-315.

[17] T. Aka-Ngnui and A. Beroual, IEEE Transactions on Dielectrics and Electrical Insulation, 13, 3 June (2006) 572-579.

[18] H. Fujita, S. Kanazawa, K. Ohtani, A. Komiya, T. Kaneko, T. Sato, Journal of Applied Physics, 116 (2014) 213301-1 - 213301-12.

[19] T. A. Ngnui and A. Beroual, J. Phys. D: Appl. Phys., 34 (2001) 794-805.

[20] H. H. Kim, Y. Teramoto, T. Hirakawa, N. Negishi, A. Ogata, Inte. J. of Plas. Envir. Sci. and Tech., 7, 2 July (2013) 109-114.

[21] Suwarno, Research Journal of Applied Sciences, 4, 4 (2009) 134-141.
[22] B. M. Cox and W. T. Williams, J. Phys. D, 10 (1977) L 5- L 9.
[23] A. L. Kupershtokh and D. I. Karpov, ISSN 1063-7850, Technical Physics Letters, 32, 5 (2006) 406-409.
[24] M. I. Quresh, A. Beroual, E. A. Al. Ammar, Inter. Journal of Phy. Sci., 9, 13 (2014) 292-301.