Modelling of second mode positive streamer in cyclohexane by considering optimized electron saturation velocity

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Abstract
Experimental and modelling study of the pre-breakdown phenomenon in dielectric liquids, generally called ‘streamers’, is vital for the application of liquids in high voltage and power dense devices. Streamer is characterized into four modes by average propagation velocity, among which the second mode streamer is responsible for breakdowns at a wide range of gap distances and voltage levels. The stable propagation velocity of around 2 km s$^{-1}$ is one of the key characteristics of the second mode streamer. The most recent study found that streamer branching is not the main reason for the stable velocity of second mode streamer as was assumed previously. Besides, one major drawback of the existing charge-drift model of the second mode streamer is the over-estimation of electron velocity, which leads to the much higher streamer propagation velocity in simulation than that observed in experiments. In this paper, restriction of streamer propagation velocity by using electron saturation velocity (ESV) is found to be the key reason for the stable propagation velocity of the second mode streamer. The charge-drift model is modified by considering different ESVs. It is found that reducing ESV from 30 km s$^{-1}$ to 2.5 km s$^{-1}$ in simulation can greatly constrain positive streamer propagation velocity from 4.15 km s$^{-1}$ to 0.50 km s$^{-1}$ in cyclohexane. When ESV is set to be 7.5 km s$^{-1}$ in cyclohexane, the streamer propagation velocity in simulation increases from 1.59 km s$^{-1}$ at 80 kV (below breakdown voltage) to 1.91 km s$^{-1}$ at 100 kV (near to acceleration voltage), which closely matches the experimental observations.

Keywords: modelling, dielectric liquids, positive streamer, electron saturation velocity, streamer propagation velocity

(Some figures may appear in colour only in the online journal)

1. Introduction
The study of pre-breakdown phenomenon in dielectric liquids, known as ‘streamer’, is generally aimed at understanding the involved physical mechanisms of a breakdown process, developing and testing new dielectric liquids and providing insight for insulation design of high voltage and power dense devices [1]. In many configurations, it was observed that positive streamers are more dangerous for high voltage insulation [2, 3]. Up to now, most studies on streamers were conducted by experiments while the underlying mechanisms of streamer initiation and propagation are not fully understood. According to average streamer propagation velocities, four kinds of streamer modes, namely 1st mode (∼0.1 km s$^{-1}$), second mode (∼2 km s$^{-1}$), 3rd mode (∼10 km s$^{-1}$) and 4th
 (>100 km s\(^{-1}\)) mode, are defined to describe different streamer characteristics, among which the second mode streamer is more commonly observed [1, 4] and is responsible for breakdown at a wide range of gap distances and voltage levels [3, 5–8]. Although streamer is a combination of low-density phase and liquid phase, it is also argued that the mechanism dominating streamer velocity must remain in the liquid phase [1].

When applied voltage rises from below breakdown voltage \(V_b\) to acceleration voltage \(V_a\), average propagation velocity of streamer in cyclohexane keeps relatively stable at 1.5–2 km s\(^{-1}\) [5]. It was also found that the addition of additives of pyrene with lower ionization potential than solvent decreases \(V_b\) and increases \(V_a\) without changing streamer velocity [5]. The reason of the stable velocity of second mode streamer in macroscopic view was assumed to be the increase of branching extent when applied voltage magnitude is increased [9, 10]. However, recent study [11] showed that increasing pressure during streamer propagation, which decreases streamer branching extent, can hardly affect \(V_a\). This result indicated that the increase of branching extent from a macroscopic view may not be the underlying mechanism for the stable velocity of second mode streamer. Therefore, it is necessary to identify new mechanism to explain this phenomenon.

The existing charge-drift model for streamer simulation [12–17] considers the movement of different kinds of charge carriers under the electric field based on ion-drift model [18], in which the velocity of movement of electric field peak is regarded as streamer velocity. The effects of voltage excitation and electrode geometry on the characteristics of second mode streamer in mineral oil were simulated by assuming that molecular ionization dominates streamer process [14, 15]. However, as shown in figure 1 which is derived according to [14, 15], under voltage level of 130 kV (<\(V_a\)) and gap distance of 25 mm, although average streamer velocity is in the range of second mode streamer, instantaneous streamer velocities show an increasing trend indicating that streamer may go beyond the second mode after further propagation. As for the remaining five cases in figure 1 [14, 15], even average streamer velocities are higher than that for second mode Therefore, improvement of the charge-drift model is necessary to solve this problem.

In this paper, electron saturation velocity (ESV) is involved to explain and model the stable velocity of second mode positive streamer. The effect of ESV was once considered in [17]. However, the mobility of electrons under low electric field is 41 times larger than [16, 19], which leads to an unreasonably abrupt velocity increase during streamer propagation [17]. In this paper, streamer in cyclohexane is simulated using the charge-drift model using the same needle-plane geometry specified in an experiment [5]. A detailed explanation on the factors affecting positive streamer velocity is first presented. Secondly, the streamer propagation dynamics in simulation such as electric field distribution and streamer head radius are explained in detail. Then, a sensitivity study on the effects of different ESVs on streamer properties, such as propagation velocity, channel radius is carried out. Finally, streamer velocities under a wide range of voltage magnitudes are modelled and compared with experimental results in [5].

\[ \nabla^2 V = - \frac{\rho_+ + \rho_- + \rho_e}{\varepsilon_0 \varepsilon_r}, \quad (1) \]

\[ \frac{\partial \rho_+}{\partial t} + \nabla \cdot (\mu_+ \rho_+ \vec{E}) = \mu_+ \rho_+ \frac{R_{+e}}{q} + \frac{\rho_+ \rho_- R_{+-}}{q}, \quad (2) \]

\[ \frac{\partial \rho_-}{\partial t} + \nabla \cdot (\mu_- \rho_- \vec{E}) = -G \left( \frac{\rho_e}{\tau_a} - \frac{\rho_+ \rho_- R_{+-}}{q} \right), \quad (3) \]

\[ \frac{\partial \rho_e}{\partial t} + \nabla \cdot (\mu_e \rho_e \vec{E}) = \frac{\rho_e}{\tau_a} - \frac{\rho_+ \rho_- R_{+-}}{q}, \quad (4) \]

where \(V\) represents voltage, \(\rho_+\), \(\rho_-\), \(\rho_e\) are the charge density of positive ions, negative ions, and electrons respectively. \(\vec{E}\) is local electric field. \(G \left( \frac{\rho_e}{\tau_a} \right)\) represents electric field dependent charge generation rate which is assumed to be molecular ionization according to [14, 15, 17, 20] and has the form given as equation (5). The meanings and values of other parameters in equations (1)–(5) are summarized in table 1.

\[ G = \frac{q^2 n_a a |E|}{\hbar} \cdot \exp \left( -\pi^2 m^* a \left( \frac{\Delta_0 - \gamma \sqrt{|E|}}{q} \right)^2 / q \hbar^2 |E| \right). \quad (5) \]

Needle-plane geometry with needle tip radius of 40 \(\mu m\) and gap distance of 50 mm is used in simulation as shown
Factors affecting positive streamer velocity

Positive streamer is accepted to be composed of low-density phase and liquid phase according to [26, 27] but the factors that affect streamer velocity are believed to mainly happen in the liquid phase [1]. A schematic diagram of streamer propagation is shown in figure 3. The positive needle tip is shown on the left-hand side. Streamer is composed of low-density phase (light blue area) and liquid phase (sky blue area) while the dark blue area represents the dielectric liquid at streamer tip where local electric filed is the highest and ionization happens.

During streamer propagation, molecular ionization happens at streamer tip, which generates positive ions and electrons. Under positive polarity, electrons are pulled towards the positive needle with a much faster velocity than positive ions being pushed to an opposite direction due to their differences in charge mobility and polarity. Some electrons are also attached to the neutral molecules to form negative ions during the movement. The separation of positive and negative charges for a positive streamer leaves a positive space charge cluster at the streamer tip, which further enhances the electric field and pushes the electric field peak to move forward. Therefore, the movement of electric field peak in simulation represents the propagation of streamer tip. The movement of charges, mainly highly mobile electrons, can generate Joule heating which contributes to the temperature rise of local liquid due to heat accumulation. Therefore, streamer channel close to the
ionizing tip is still liquid phase while the other parts gradually become low-density phase after heat accumulation.

From the description above, it can be concluded that how fast the electric field at streamer tip moves forward determines streamer velocity. From a microscopic view, the movement velocity of electric field peak during streamer propagation is mainly dominated by the positive space charge peak behind it. When the positive space charge peak forms more quickly, the electric field peak can be enhanced faster and move farther correspondingly, which means streamer velocity is faster. Considering the formation process of positive space charge peak, two parameters should be taken into consideration, namely electron velocity $v_e = \mu_e E$ and electron attachment time $\tau_a$. Electrons with smaller $v_e$ cannot leave the ionizing zone fast enough to form the positive space charge peak. Besides, smaller $\tau_a$ represents an easier attachment to neutral molecules to form negative ions. The velocity of generated negative ions is even slower than electrons, which further slows down the formation of positive space charge peak. Therefore, both smaller $v_e$ and $\tau_a$ can constrain positive streamer velocity. Because second mode streamer exists over a wide range of applied voltage magnitudes, the highly electric-field-dependent nature of electron velocity is assumed to be the key reason for the stable velocity of second mode positive streamer.

Under low to moderate electric field, $\mu_e$ is calculated to be $\mu_{e,0} = 1 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ [28, 29] and electron velocity $v_e$ equals $\mu_{e,0} E$ where $E$ is local electric field. Previous charge-drift model [12, 13, 16] assumes constant electron mobility under electric field ranging from zero to several MV cm$^{-1}$ shown as the black line (labelled as ‘No ESV’) in figure 4. However, electron velocity may reach saturation velocity under extremely high electric field possibly due to the transfer of energy and momentum from electrons to phonons and the increase of effective electron mass based on well-known Shockley theory and its following studies [30–33]. ESV has been confirmed in different dielectric liquids by [34, 35] and is estimated to be on the order of 10 km s$^{-1}$ which occurs at electric field over ~1 MV cm$^{-1}$ in liquid argon [36]. Although the electron velocity without considering ESV may reach 30–40 km s$^{-1}$ at ~3–4 MV cm$^{-1}$ in previous simulations [12–15], it is worth examining whether this is too high for electron velocity in cyclohexane.

Within a wide range of electric field magnitudes, the widely adopted empirical equation to describe electron velocity in semiconductors is shown in equation (6) [37]. For simplification, $\beta$ is set to be 1 in this paper, which gives ESV at extremely high electric field equal to $\mu_{e,0} E_0$. The simplified expression form of ESV in equation (6) is the same as that adopted in [17] shown in equation (7) when $v_1/E_1 = \mu_{e,0}$. A comparison between ESV calculated by equation (6) and [17] is shown in figure 4. It is found that $v_e$ increases linearly with electric field at low to moderate electric field and then gradually reaches ESV, which is in the similar trend as mentioned in [35]. However, the values of $v_1$ and $E_1$ are selected separately in [17], which makes the electron mobility at low to moderate electric field 41 times larger than [16, 19]. Therefore, the form of equation (6) is more representative and hence adopted in this paper.

$$v_e = \mu_{e,0} \frac{E}{(1 + (E/E_0)^\beta)^{1/\beta}}, \quad (6)$$

$$v_e = v_1 \frac{E}{E_1 + E}, \quad (7)$$

where $E_0$, $\beta$, $v_1$ and $E_1$ are fitting parameters. $v_1 = 41 \text{ km/s}$ and $E_1 = 0.1 \text{ MV cm}^{-1}$ are used in [17].

4. Simulation results

4.1. Descriptions on streamer dynamics

Since the velocity of the movement of electric field peak is generally regarded as the velocity of streamer in simulation, the distribution of electric field at different time with voltage magnitude of 100 kV when ESV is set to be 7.5 km s$^{-1}$ is shown in figure 5. The reason for using ESV of 7.5 km s$^{-1}$ will be explained from sections 4.2 to 4.4. In figure 5(a), initially with the increase of voltage during the rise time from 0 to 180 ns, the electric field magnitude along symmetric axis from needle tip into cyclohexane gradually rises, which is similar with Laplace field. Electric field peak leaves the needle tip and propagates into cyclohexane at 180 ns with its magnitude equal to 3.07 MV cm$^{-1}$ due to the effects of the accumulated space charges generated by molecular ionization. The electric field peak magnitude shows a first increasing and then decreasing trend until it reaches a stable magnitude which equals ~3.7 MV cm$^{-1}$ during its propagation. Since this paper only considers one single streamer branch due to the limitation of 2D-axisymmetric model, the streamer shape looks like a tube during propagation as shown in figure 5(b), which can
be regarded as an extension of positive needle tip into cyclo-
hexane. According to the calculation method used in [16, 22],
the average voltage drop of the flat electric field area inside
streamer channel is \( \sim 1.76 \times 10^7 \) V m\(^{-1}\).

Due to lack of discussion on how to define streamer radius
in previous simulations, a sensitivity discussion on streamer
radius during streamer propagation is shown in figure 6.
Streamer radius is defined as the maximum radius of the
boundary of the pre-defined electric field tube at streamer
head. The boundary of pre-defined electric field tube is from
30\% to 70\% of maximum electric field at the streamer tip \( E_{\text{max}} \)
as shown in the 2D distribution of electric field inside figure 6.
It is found that during streamer propagation, streamer radius
keeps relatively stable at different streamer lengths while the
percentile of the pre-defined electric field tube at streamer head
greatly affects streamer radius. For streamer length at 0.6 mm,
streamer radius decreases from 68.0 \( \mu \)m to 33.7 \( \mu \)m with pre-
defined percentile increasing from 30\% to 70\%. In the follow-
ing, streamer radius is reported as the boundary of electric
field tube at 50\% \( E_{\text{max}} \), at streamer head when streamer length
equals 0.6 mm.

Figure 6. (a) Streamer head radius at different streamer lengths
under different measurement standard. (b) 2D distribution of
predefined electric field tube at streamer head with streamer length
at 0.6 mm and standard from 30\% to 70\% \( E_{\text{max}} \). Voltage magnitude
equal to 100 kV and ESV equal to 7.5 km s\(^{-1}\).

Instantaneous streamer velocity at different streamer
lengths and the corresponding peak electric field magnitude
and space charge density at streamer tip are shown in figure 7.
Space charge density equals the sum of the charge dens-
ity of positive ions, negative ions and electrons. It shows
that instantaneous streamer velocity first increases to around
4 km s\(^{-1}\) and then decreases to a relatively stable value at
\( \sim 1.91 \) km s\(^{-1}\). This first increasing and then decreasing trend
to a stable stage phenomenon of streamer velocity has also
been observed in experiments based on high resolution shock-
wave observation [38]. The stable stage of streamer velocity is
termed as propagation velocity in this paper.
Figure 8. Time-dependent distribution of electric field peak magnitude and the distance $d_{E\rho}$ between electric field peak and space charge density peak during streamer propagation with voltage magnitude equal to 100 kV. ESV = 7.5 km s$^{-1}$.

Figure 9. Distribution of electric field and space charge density along z-axis from 200 ns to 270 ns.

It is important to observe that the variation of streamer velocity is correlated to the variation of local electric field magnitude at streamer tip, which supports the argument in section 3 that positive streamer velocity is partially dependent on electric field dependent $v_s$ as is discussed. The variation of the electric field peak magnitude could be explained by the distance between local electric field peak position and space charge density peak position at streamer tip, $d_{E\rho}$. The corresponding time-dependent relationship between electric field peak magnitude and $d_{E\rho}$ during streamer propagation is shown in figure 8. The electric field and space charge distributions along z-axis from needle tip into cyclohexane from 200 ns to 270 ns are shown in figure 9. It is found that electric field peak is always some distance ahead of space charge density peak. As shown in figures 7 and 8, the electric field peak leaves needle tip after 180 ns at 3.07 MV cm$^{-1}$ while space charge density peaks stays at needle tip so that the distance between them, $d_{E\rho}$, increases. With time increasing, electric field peak moves further into cyclohexane while the space charge density peak still keeps at needle tip. From 0 ns to 250 ns, only the volume of space charge density increases as shown in figure 9, which leads to a consistent increase in the distance $d_{E\rho}$. The electric field distribution in cyclohexane is also mainly determined by Laplace field induced by applied voltage rather than space charge induced electric field as shown in figure 10. At 250 ns, the position of peak space charge density switches from needle tip to to the position just behind electric field peak, which leads to a sudden decrease in the distance $d_{E\rho}$ and from now on space charge induced electric field begins to dominate the total electric field in cyclohexane. Afterwards, the variation of distance $d_{E\rho}$ has an opposite relationship with that of electric field peak magnitude. The distance $d_{E\rho}$ first decreases to its smallest value $\sim$1.5 $\mu$m at 325 ns when electric field magnitude also reaches its highest value $\sim$4.4 MV cm$^{-1}$. Then the distance $d_{E\rho}$ gradually increases to a stable value $\sim$3.5 $\mu$m when electric field magnitude also decreases to $\sim$3.7 MV cm$^{-1}$.

4.2. Effects of ESV on streamer

The effect of ESV on instantaneous streamer velocity is shown in figure 11. The corresponding streamer propagation velocity and voltage drop inside streamer channel are shown in figure 12. When ESV reduces from 30 km s$^{-1}$ to 2.5 km s$^{-1}$, streamer propagation velocity also decreases from
Effects of electron saturation velocity on streamer propagation velocity and voltage drop with voltage magnitude equal to 100 kV. The voltage drop inside streamer channel decreases from 34.80 kV mm$^{-1}$ to 10.63 kV mm$^{-1}$. In this paper, matching streamer propagation velocity with experiments is more important than matching voltage drop because the voltage drop might be related with low-density channel formation inside streamer body which is not simulated in this paper. Streamer radius also increases from 18 µm to 73.6 µm with the decrease of ESV as shown in figure 13. Streamer radius of 44 µm in simulation is also close to the experimental observations of second mode streamer channel radius of ∼50 µm in [5, 27]. Therefore, ESV equal to 7.5 km s$^{-1}$ is selected as the best optimized value to fit experimental results with voltage magnitude at 100 kV.

Figure 13. Effects of electron saturation velocity on streamer radius during streamer propagation with voltage magnitude equal to 100 kV. Streamer radius is defined as boundary of 50% $E_{\text{max}}$ at streamer head at 0.6 mm.

Figure 14. Comparison of streamer propagation velocity in simulation with experiments under different voltage magnitudes. Black dots are from [5].

4.3. Effects of applied voltage on streamer

The optimized ESV value of 7.5 km s$^{-1}$ based on experiment at $V = 100$ kV is further applied to other voltage levels ranging from 80 kV to 95 kV to confirm the optimized model. The effect of applied voltage magnitudes on streamer propagation velocity is shown in figure 14 which is also compared with experimental results in [5]. With the magnitude of applied voltage increasing from 80 kV (below $V_b$) to 100 kV (close to $V_a$), streamer propagation velocity increases slightly from ∼1.59 km s$^{-1}$ to ∼1.91 km s$^{-1}$, which shows a good agreement with experimental results of cyclohexane in [5]. The deviation between simulation and experimental results is smaller than 3%. Besides, as shown in figure 15, streamer radius also shows an increasing trend from 37.5 µm to 44.0 µm when the applied voltage increases.
4.4. Discussion

The aim of this paper is to explain the reason for the stable velocity of second mode positive streamer by using ESV. It has been confirmed that ESV can successfully constrain streamer velocity to a reasonable level when compared with experimental results. Therefore, it is necessary to further explanation whether ESV could happen in cyclohexane during streamer propagation.

Due to lack of experiments on confirming ESV in cyclohexane to the authors’ best knowledge, only theoretical analysis is presented here. According to the argument in [39], at sufficiently high electric filed, when the electrons gain more energy than $k_BT$ between collisions with molecules, electron mobility goes down, where $k_B$ is Boltzmann constant and $T$ is local temperature. As described in the introduction, streamer is consisted of low-density phase and liquid phase and the mechanism dominating streamer velocity should happen in the liquid phase [1, 26, 27]. Assuming the maximum temperature at streamer tip under atmosphere pressure in cyclohexane is the same as the liquid boiling temperature 353 K [34], $k_BT$ equals 0.030 eV. Under local electric field equal to 3.7 MV cm$^{-1}$ at streamer tip according to figure 7, an electron could gain $W_e = eEa = 0.111$ eV before collision with neutral molecules, which is high enough to justify the existence of ESV.

Besides, due to the complexity of streamer nature and the challenge of computational resource, some phenomena have been simplified and are further discussed as follows.

The first simplification is that the model in this paper does not consider the physics inside low-density phase of streamer channel. As is mentioned according to figure 3, low-density phase inside streamer channel will be formed due to the temperature rise induced by Joule heating. Inside low-density area, the values of parameters, such as charge mobility, charge generation and recombination rate and the relative permittivity of dielectric material will all change accordingly [16], which are not the same as the parameters in liquid phase. The main difficulties of simulating streamer with low-density channel are the complexity of physics involved and the hard convergence when solving the highly non-linear partial differential equations. Besides, when considering the factors affecting streamer velocity by low-density phase of streamer, the most important effect from a macroscopic view is to lower the voltage drop inside streamer channel. The voltage drop inside streamer channel is calculated to be $\sim 2 \times 10^{6}$ V m$^{-1}$ in cyclohexane in experiments [5] while it is $\sim 1.76 \times 10^{7}$ V m$^{-1}$ from the simulation in this paper when ESV is assumed to be 7.5 km s$^{-1}$ under voltage magnitude of 100 kV. The higher voltage drop would decrease voltage potential at streamer tip and then slightly slow down the streamer velocity. Therefore, the true ESV might be a bit smaller than estimated this paper.

Secondly, this paper does not simulate the effects of electron attachment time $\tau_a$ on streamer velocity. $\tau_a$ is closely related with the components and purity of the dielectric liquids. $\tau_a$ is found to be $\sim 500$ ns in cyclohexane [40] and $\sim 100$ ns in hydrocarbons [34, 41] in experiments while it is argued to be much smaller and also electric field dependent in simulation [42]. The value $\tau_a = 200$ ns is somewhat a compromise for different values in the literature. The further effects of $\tau_a$ in liquid is unable to simulate in this paper because too small $\tau_a$ will increase voltage drop significantly when excluding the low-density phase inside streamer channel.

Thirdly, this paper only simulates the propagation of a single streamer branch instead of streamer with multiple branches due to the limitation of 2D-axisymmetric model and demanding computational resources in 3D model. Although streamer branching may have some shielding effects on the velocity of streamer branches to some extent, the recent results in [11], as is discussed in the introduction, it is indicated that the shielding effects of streamer branching is not the dominant reason to constrain streamer velocity. Therefore, it is acceptable to only simulate a single streamer channel.

Based on the descriptions above, although there are two limitations on simulating the low-density channel inside streamer channel and the multiple streamer branches, this paper presented a valuable simulation on the stable propagation velocity of second mode positive streamer which shall not be dominated by the two limitations but the electron velocity in the liquid phase of streamer.

5. Conclusion

Positive second mode streamer in cyclohexane is simulated in COMSOL Multiphysics and compared with experimental results in [5]. The variation of instantaneous streamer velocity is found to be positively related with the electric field magnitude at the streamer tip. The magnitude of electric field at the streamer tip first increases and then decreases to a relatively stable value, which is explained by the peak distance between electric field and space charge density during streamer propagation. The mechanism of the stable propagation velocity of second mode positive streamer in cyclohexane is thought to be the constrain of ESV. Simulation found that reducing ESV from 30 km s$^{-1}$ to 2.5 km s$^{-1}$
decreases streamer propagation velocity from 4.15 km s\(^{-1}\) to 0.50 km s\(^{-1}\). Besides, streamer channel radius also increases from 18 \(\mu\)m to 73.6 \(\mu\)m. ESV of 7.5 km s\(^{-1}\) is optimized according to experimental observation of streamer velocity at 100 kV. The streamer model with ESV of 7.5 km s\(^{-1}\) is further applied to other different voltage levels. Streamer propagation velocity in simulation increases from 1.59 km s\(^{-1}\) at 80 kV (below breakdown voltage) to 1.91 km s\(^{-1}\) at 100 kV (close to acceleration voltage), which all match closely to the experimental observations under the same condition in [5].

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References

[1] Lesaint O 2016 Prebreakdown phenomena in liquids: propagation ‘modes’ and basic physical properties J. Phys. D: Appl. Phys. 49 144001
[2] Kamata Y and Kako Y 1980 Flashover characteristics of extremely long gaps in transformer oil under non-uniform field conditions IEEE Trans. Electr. Insul. 1 18–26
[3] Lesaint O, Saker A, Gournay P, Tobazeon R, Aubin J and Mailhot M 1998 Streamer propagation and breakdown under ac voltage in very large oil gaps IEEE Trans. Dielectr. Electr. Insul. 5 851–9
[4] Heber R 1988 The Liquid State and Its Electrical Properties (NATO ASI Series vol B 193) (New York: Plenum)
[5] Lesaint O and Jung M 2000 On the relationship between streamer branching and propagation in liquids: influence of pyrene in cyclohexane J. Phys. D: Appl. Phys. 33 1360
[6] Liu Q and Wang Z D 2011 Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage IEEE Trans. Dielectr. Electr. Insul. 18 285–94
[7] Lu W, Liu Q and Wang Z D 2017 Pre-breakdown and breakdown mechanisms of an inhibited gas to liquid hydrocarbon transformer oil under negative lightning impulse voltage IEEE Trans. Dielectr. Electr. Insul. 24 2809–18
[8] Shen S, Liu Q and Wang Z 2019 Effect of electric field uniformity on positive streamer and breakdown characteristics of transformer liquids IEEE Trans. Dielectr. Electr. Insul. 26 1814–22
[9] Lesaint O and Massala G 1998 Positive streamer propagation in large oil gaps: experimental characterization of propagation modes IEEE Trans. Dielectr. Electr. Insul. 5 360–70
[10] Massala G and Lesaint O 1998 Positive streamer propagation in large oil gaps: electrical properties of streamers IEEE Trans. Dielectr. Electr. Insul. 5 371–81
[11] Linjell D, Lundgaard L E and Unge M 2019 Pressure dependent propagation of positive streamers in a long point-plane gap in transformer oil 2019 IEEE 20th Int. Conf. on Dielectric Liquids (ICDL) pp 1–3
[12] Qian J, Joshi R P, Schamiloglu E, Gaudet J, Woodworth J R and Lehr J 2006 Analysis of polarity effects in the electrical breakdown of liquids J. Phys. D: Appl. Phys. 39 359–69
[13] Hwang J G 2010 Elucidating the mechanisms behind pre-breakdown phenomena in transformer oil systems PhD Thesis (Cambridge, MA, USA: Massachusetts Institute of Technology)
[14] Jadidian J, Zahn M, Lavesson N, Widlund O and Borg K 2012 Effects of impulse voltage polarity, peak amplitude, and rise time on streamers initiated from a needle electrode in transformer oil IEEE Trans. Plasma Sci. 40 909–18
[15] Jadidian J, Zahn M, Lavesson N, Widlund O and Borg K 2012 Impulse breakdown delay in liquid dielectrics Appl. Phys. Lett. 100 192910
[16] Naidis G V 2015 Modelling of streamer propagation in hydrocarbon liquids in point-plane gaps J. Phys. D: Appl. Phys. 48 195203
[17] Jadidian J, Zahn M, Lavesson N, Widlund O and Borg K 2014 Abrupt changes in streamer propagation velocity driven by electron velocity saturation and microscopic inhomogeneities IEEE Trans. Plasma Sci. 42 1216–23
[18] Gafvert U, Jakstas A, Tornkvist C and Walfridsson L 1992 Electrical-field distribution in transformer oil IEEE Trans. Electr. Insul. 27 647–60
[19] Naidis G V 2015 Modeling of subnanosecond discharge in hydrocarbon liquid IEEE Trans. Plasma Sci. 43 3138–41
[20] Jadidian J, Zahn M, Lavesson N, Widlund O and Borg K 2013 Stochastic and deterministic causes of streamer branching in liquid dielectrics J. Appl. Phys. 114 063301
[21] Gee N and Freeman G R 1992 Free ion yields, electron thermalization distances, and ion mobilities in liquid cyclic hydrocarbons: cyclohexane and cis and trans-decalin J. Chem. Phys. 96 586–92
[22] O’Sullivan F 2007 A model for the initiation and propagation of electrical streamers in transformer oil and transformer oil based nanofluids PhD Thesis (Cambridge, MA, USA: Massachusetts Institute of Technology)
[23] Zahn M 2003 Electromagnetic Field Theory: A Problem Solving Approach (Malabar, FL: Krieger)
[24] Jadidian J 2013 Charge transport and breakdown physics in liquid/solid insulation systems PhD Thesis (Cambridge, MA, USA: Massachusetts Institute of Technology)
[25] Casanovas J, Grob R, Delacroix D, Guelucci J P and Blanc D 1981 Photoconductivity studies in some nonpolar liquids J. Chem. Phys. 75 4661–8
[26] Lesaint O and Gournay P 1994 On the gaseous nature of positive filamentary streamers in hydrocarbon liquids. I: influence of the hydrostatic pressure on the propagation J. Phys. D: Appl. Phys. 27 2111
[27] Gournay P and Lesaint O 1994 On the gaseous nature of positive filamentary streamers in hydrocarbon liquids. II: propagation, growth and collapse of gaseous filaments in pentane J. Phys. D: Appl. Phys. 27 2117
[28] Allen A O 1976 Drift Mobilities and Conduction Band Energies of Excess Electrons in Dielectric Liquids (Gaithersburg, ML: U.S. Dept. of Commerce, National Bureau of Standards)
[29] Schmidt W F 1977 Electron mobility in nonpolar liquids: the diffusion coefficient of electrons in Si from 77°K to 500°K Natu. Cimento 3 728–35
[32] Costato M and Reggiani L 1970 Electron drift velocity and related phenomena in Si Phys. Status Solidi b 42 591–602
[33] Komirenko S, Kim K, Kochelap V and Stroscio M 2002 Coherent LO phonons generated by high-velocity electrons in two-dimensional channels and their impact on carrier transport Proc. 2nd IEEE Conf. on Nanotechnology pp 1–4
[34] Tobazeon R 1994 Prebreakdown phenomena in dielectric liquids IEEE Trans. Dielectr. Electr. Insul. 1 1132–47
[35] Holroyd R A and Schmidt W F 1989 Transport of electrons in nonpolar fluids Annu. Rev. Phys. Chem. 40 439–68
[36] Lehr J M, Agee F J, Copeland R and Prather W D 1998 Measurement of the electric breakdown strength of transformer oil in the sub-nanosecond regime IEEE Trans. Dielectr. Electr. Insul. 5 857–61
[37] Canali C, Majni G, Minder R and Ottaviani G 1975 Electron and hole drift velocity measurements in silicon and their empirical relation to electric field and temperature IEEE Trans. Electron Devices 22 1045–7
[38] Shen S, Liu Q and Wang Z D 2020 Shockwave characteristics of streamer propagation in insulating liquids under positive lightning impulse IEEE Trans. Dielectr. Electr. Insul. in press
[39] Schmidt W F and Allen A O 1970 Mobility of electrons in dielectric liquids J. Chem. Phys. 52 4788–94
[40] Denat A, Gosse J P and Gosse B 1988 Electrical conduction of purified cyclohexane in a divergent electric field IEEE Trans. Electr. Insul. 23 545–54
[41] Tobazeon R 1993 Prebreakdown phenomena in dielectric liquids IEEE 11th Int. Conf. on Conduction and Breakdown in Dielectric Liquids pp 172–83
[42] Aljure M, Becerra M and Karlsson M E 2019 On the injection and generation of charge carriers in mineral oil under high electric fields J. Phys. Commun. 3 035019