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Modeling the Transition to Fast Mode Streamers in Dielectric Liquids

I. Madshaven,* P.-O. Åstrand,* O. L. Hestad,† M. Unge,‡ O. Hjortstam‡
*Departement of Chemistry, NTNU - Norwegian University of Science and Technology, 7491 Trondheim, Norway
†SINTEF Energy Research, 7491 Trondheim, Norway
‡ABB Corporate Research, 72178 Västerås, Sweden

***Abstract*—A simplified model for photoionization, modeling fast streamer propagation, is combined with an existing model for slow streamers, based on electron avalanches. Transitions from fast mode to slow mode, and from slow mode to fast mode, are investigated.**

I. INTRODUCTION

Important characteristics of streamers include the polarity, the propagation speed, and the topology. Positive streamers are classified into different modes by their propagation speed. While streamers in the 2nd mode propagate at speeds on the order of $\mathrm{km/s}$, the speed of 4th mode streamers may exceed 100 $\mathrm{km/s}$ [1]. The present work concerns modeling positive streamers in liquid cyclohexane, propagating in a tube, in a needle-plane gap. Streamer propagation is investigated by combining models based on electron avalanches [2] and on photoionization [3].

II. BACKGROUND

Streamer experiments are often carried out in a needle-plane geometry [1]. The strongly divergent electric field in the region close to the needle makes it possible to control where the streamer inception will occur, and to study the inception and propagation of a streamer not resulting in a complete breakdown. A streamer consists of one or more branches. The potential at the tip of each branch is dependent on the potential in the needle and the electric field in the streamer channel. The dynamics of the streamer channel is of importance, however, processes occurring at the tip of the branches, like electron avalanches [4] and photoionization, are viewed as more important. An lowered ionization potential (IP) in a strong electric field, may facilitate photoionization [5].

A. Electron avalanches

The insulating liquid comprises various chemical species. Free electrons, generated by e.g. ionizing cosmic radiation, have short lifetimes (in weak electric fields) and recombine rapidly to form neutral molecules or anions. In a strong electric field, however, free electrons are accelerated and may cause impact ionization, yielding more free electrons. The net ionization probability α is a function of the electric field strength E, and may be approximated by [4]

$$\alpha = \alpha_\mathrm{m} \exp\left(-\frac{E_\alpha}{E}\right) \tag{1}$$

where the parameters α_m and E_α are dependent on the liquid. According to the Townsend-Meek avalanche-to-streamer criterion, an avalanche becomes unstable when exceeding a critical size [6]

$$Q = \int \alpha \, \mathrm{d}\ell > Q_\mathrm{c} \tag{2}$$

where, ℓ is length, $\exp(Q)$ is the number of electrons in an avalanche, and Q_c is the Meek constant. The value of Q_c is typical 18 for hydrocarbon gases [7], while values ranging from 5 to 23 have been used for liquids [6], [8], [9].

B. Field-dependent ionization potential

The IP is the energy required to ionize a molecule from its ground state, and is an important characteristic of an insulating liquid [5], [10]. Additives with a low IP have been found to facilitate the growth of slow streamers [11] and increase the threshold for fast propagation, the acceleration voltage [1]. An electric field lowers the IP [5]. The field-dependent ionization potential $I(E)$ can be calculated for the hydrogen atom [5]

$$I(E) = I_0 - \beta \sqrt{\frac{E}{\epsilon_\mathrm{r} \, E_{a_0}}} \tag{3}$$

where, I_0 is the zero-field IP, E is the electric field, $E_{a_0} = 5.14 \times 10^{11}\,\mathrm{V/m}$, ϵ_r is the relative permittivity, and $\beta = 54.4\,\mathrm{eV}$. This equation holds qualitatively for other molecules also, where the parameter β may be fitted to results of quantum mechanical calculations [5], [12], [13].

C. Photoionization

Photoionization plays an important role in electrical discharge in gases, but its role in liquids is unclear [1]. Streamers often emit light, continuous or pulsed, especially the fast modes [14]. It has been suggested that photoionization in front of the streamer head act as a feed-forward mechanism [15] facilitating the high speed of fast streamers. However, this is difficult to confirm, since ionizing radiation is rapidly absorbed in a liquid, and thus difficult to measure.

Electronically excited states have, in most cases, relatively short lifetimes and the molecules rapidly relax to a lower state. Typically, an excited molecule will relax through one or more states to the lowest electronically excited state by emitting heat, and finally to the ground state by emitting light in the UV/VIS region. This is especially interesting when viewed in combination with the field-dependent IP, since radiation from

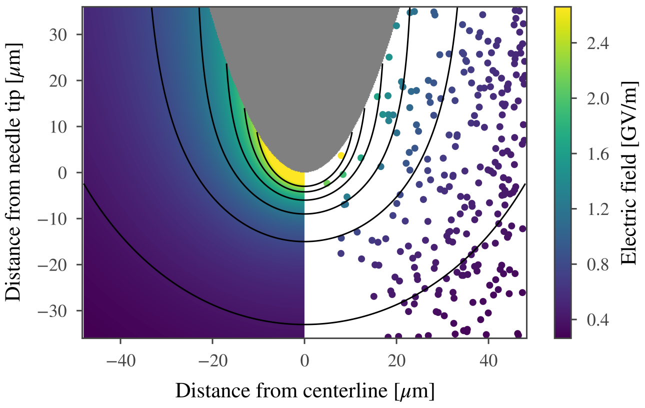

Figure 1. Initial electric field strength (left) and seeds (each marker, right). For a region close to a needle with a potential of $150\,\mathrm{kV}$, a tip radius $6.0\,\mathrm{\mu m}$ placed $50\,\mathrm{mm}$ from a grounded plane.

within the streamer (or other low-field regions) could cause ionization locally in front of the streamer, where the IP is lowered by the electric field.

III. Streamer Model

Our streamer model has been developed with the aim to capture the most important aspects of streamer inception and streamer propagation, while keeping it simple [2]. The model is built on the Townsend-Meek criterion, following the assumption that electron avalanches occur in the liquid phase [4]. In the present work, a simplified mechanism for photoionization [3] has been added to the existing model.

A. Geometry

The needle-plane geometry is represented by a hyperboloid at a constant potential, placed at a distance from a grounded plane. The Laplace equation, giving the potential and the electric field, has an analytic expression for this geometry [23]. The gap distance, the needle tip radius, and the needle potential, defines the initial electric field distribution (see Fig. 1).

Table I
Model parameters. A large gap and a theoretical liquid similar to cyclohexane.

Symbol	Magnitude	Description
d	$50\,\mathrm{mm}$	Needle-plane separation
r_p	$6.0\,\mathrm{\mu m}$	Streamer head curvature [16]
I_0	$9.0\,\mathrm{eV}$	Ionization potential [13]
ε_1	$6.0\,\mathrm{eV}$	First excitation energy [13]
β	$50.8\,\mathrm{eV}$	IP reduction parameter [13]
v_4	$100\,\mathrm{km/s}$	4th mode propagation speed [1]
E_4	$3.04\,\mathrm{GV/m}$	Threshold field for 4th mode (4)
E_s	$2.0\,\mathrm{MV/m}$	Streamer electric field [17], [18]
E_det	$1.0\,\mathrm{MV/m}$	Threshold for electron detachment
E_mul	$157\,\mathrm{MV/m}$	Threshold for electron multiplication
E_α	$1.9\,\mathrm{GV/m}$	Inelastic scattering constant [19]
α_max	$120\,\mathrm{\mu m^{-1}}$	Maximum avalanche growth [19]
Q_c	23	Meek constant [8]
μ_e	$45\,\mathrm{mm^2/Vs}$	Electron mobility [20]
μ_i	$0.3\,\mathrm{mm^2/Vs}$	Ion mobility [21]
σ	$5.0\,\mathrm{pS/m}$	Low-field conductivity [22]
Δt	$1.0\,\mathrm{ps}$	Simulation time step

B. Streamer

The streamer is modeled as a collection of hyperbolic “heads”, each representing the tip of a branch. The potential of a streamer head is calculated assuming a constant electric field between the tip of the needle and the tip of the streamer head. The tip radius of a streamer head is based on the critical radius for inception of 2nd mode streamers [16]. For a streamer with several branches, potential shielding between the heads create an extra complication. To simplify the problem, the modeled streamer consists of a single head, which is comparable to a streamer propagating in a tube [18], [24].

C. Seeds

An initial number of anions is calculated based on the low-field conductivity and the ion mobility. Such anions are included in the model as “seeds” for electrons and electron avalanches. An example of the initial distribution of seeds is shown in Fig. 1. The seeds are considered to be anions in low-field conditions, electrons in intermediate fields, and electron avalanches in high-field conditions. Seeds are moved according to their mobility, and avalanches grow according to (2). A electron avalanche reaching the Townsend-Meek criterion is considered as a part of the streamer. If this is obtained in front of the streamer head (closer to the plane), then the streamer head is moved to the location of the avalanche.

D. Photoionization

Radiation is assumed to originate in the head of the streamer channel, which consists of a hot, gaseous, and partly ionized phase [25]. The focus of the model is radiation from molecules relaxing from the lowest electronically exited state to the ground state. Previous work on the model [3] showed how a strong electric field directly in front of the streamer could enable radiation from the ground state to cause ionization. The ionization rate in front of the streamer head was used as a measure of the streamer propagation speed, and a sudden change predicted when the field-dependent IP was comparable to the first excited state. Since the ionization rate is somewhat expensive to compute, a simplified model has been implemented. If the electric field at the tip of the streamer head is above a given threshold, a constant speed is added to the streamer head (it is moved by a short distance every iteration). The threshold field E_4 is given by

$$I(E_4) = \varepsilon_1 \tag{4}$$

where ε_1 is the energy of the lowest electronically excited state (relative to the ground state).

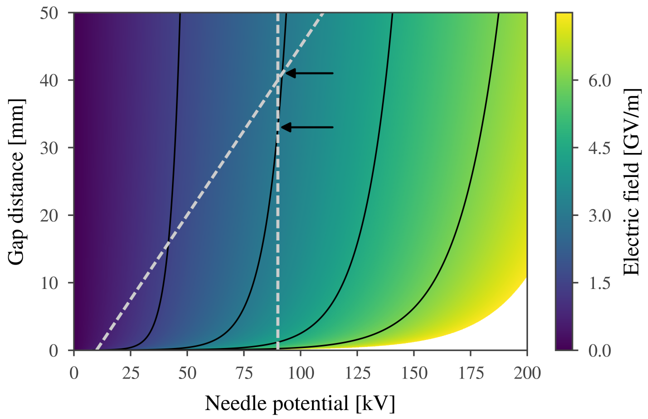

Figure 2. Electric field strength at the tip of a conducting hyperboloid with a tip curvature of $6.0\,\mu\mathrm{m}$. The dotted lines show the effect of an electric field in the channel, for a potential of $90\,\mathrm{kV}$ with $E_\mathrm{s} = 0\,\mathrm{MV/m}$, and for a potential of $110\,\mathrm{kV}$ with $E_\mathrm{s} = 2\,\mathrm{MV/m}$. The arrows indicate where the dotted lines cross the threshold for fast propagation, $E_4 = 3.04\,\mathrm{MV/m}$.

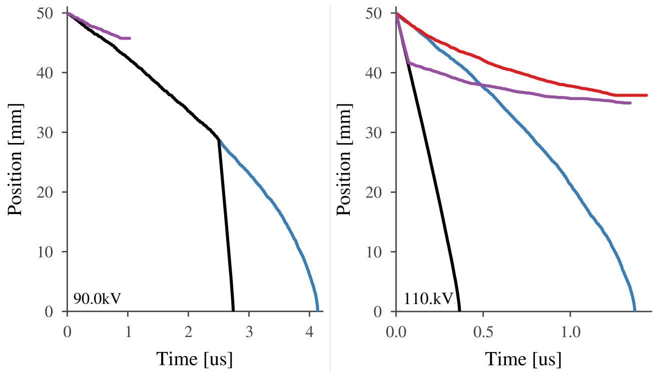

Figure 3. Streak plots showing the position of tip of the streamer for four simulations each. For $E_\mathrm{s} = 0\,\mathrm{MV/m}$ (red, purple), $E_\mathrm{s} = 2\,\mathrm{MV/m}$ (blue, black), no photoionization (red, blue), and photoionization enabled (purple, black).

E. Model Parameters

The geometry is that of a large gap with a sharp needle, and the liquid parameters are chosen for cyclohexane. The main parameters are summarized in Tab. I and are similar to those used before [2]. Here, however, the gap is larger, and parameters for photoionization are added. Additionally, the avalanche parameters (α_max and E_α) are taken from Naidis [19]. The excitation energy and IP are reduced by about $1\,\mathrm{eV}$ for a molecule in a liquid as compared with the gas phase [26].

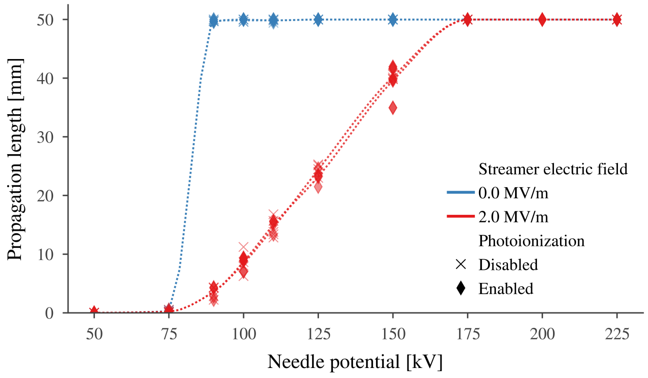

Figure 4. Streamer propagation length. Each marker is a simulation. The trend lines are interpolated to the averages.

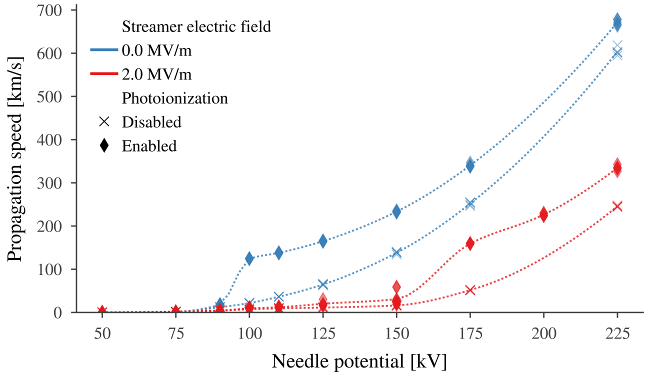

Figure 5. Average streamer propagation speed. Each marker is a simulation. The trend lines are interpolated to the averages.

IV. RESULTS

The result of the simulations may be interpreted from Fig. 2. For electron avalanches to cause propagation, the Townsend-Meek criterion must be reached in front of the streamer tip, which presumably requires a field strength greater than E_α. Propagation by photoionization occurs when the field strength is greater than E_4. Considering the case where the channel is perfectly conducting ($E_\mathrm{s} = 0$), a streamer may start slow and speed up at some point during propagation. The change should occur at about $33\,\mathrm{mm}$ for $90\,\mathrm{kV}$. Conversely, by considering $E_\mathrm{s} = 2\,\mathrm{MV/m}$, the streamer propagation speed may slow down at a certain point. For $110\,\mathrm{kV}$, the electric field at the tip drops below E_4 at about $42\,\mathrm{mm}$.

At $90\,\mathrm{kV}$, the streamer quickly stops if there is a potential drop in the channel (Fig. 3). Without a potential drop, the streamer is able to close the gap, starting slow and finishing fast. Increasing the potential to $90\,\mathrm{kV}$, enables the streamer to propagate the entire gap in a fast mode, however, with $E_\mathrm{s} = 2\,\mathrm{MV/m}$, the streamer slows down and stops instead.

Fig. 4 shows that the propagation length is mainly dependent on the needle potential and the electric field in streamer channel. Increasing the voltage increases the propagation speed, see Fig. 5. A lower potential drop enables further propagation at low voltages, and results in an overall increase in speed. Enabling photoionization adds a constant contribution to the speed above a threshold voltage dependent on the conductivity.

V. DISCUSSION

Fig. 2 explains most of the behavior of the simplified model, and it can also be used to qualitatively explain a more complex model, with several streamer heads and a fluctuating electric field in the streamer channel. Adding more streamer heads implies shielding, reducing the electric field in front of each head. A streamer could initiate fast, with a single head, and slow down when another head is added. Conversely, a slowly propagating streamer with many heads could speed up if a head is removed. It is also clear that the conduction of the channel is important for large gaps. Fast-moving streamers presumably have lower fields than slow-moving streamers [1].

The propagation voltage (see Fig. 4) is too high for slow streamers [1], as expected [2]. Given a lower propagation voltage, the simulations could have shown streamers initiating in fast mode, slowing down, and closing the gap. However, for streamers propagating in tubes, the acceleration voltage is close to the breakdown voltage [18], as found here. The propagation speed (see Fig. 5) for the "slow" streamers is too high at high voltages. That is, however, for the current model, which is restricted to a single head, and enabling branching would slow down the streamer.

Modeling photoionization by simply adding a speed above a threshold field is a grave simplification. One of the goals of the present work was to investigate how this model for photoionization worked in combination with the existing model based on electron avalanches. To improve the model, a good approximation of the amount of radiation available from the streamer head is needed, and based on this, the propagation speed may be estimated [3].

VI. CONCLUSION

The presented model shows how several features of streamer propagation may be explained by the means of two simple mechanisms. The results show streamers transitioning from slow to fast for highly conducting channels as the electric field strength at the head increases during propagation. Conversely, for less conducting channels, a transition from fast to slow mode is observed as the electric field decreases. The acceleration voltage is close to the breakdown voltage, as it should be for streamers in tubes. An improved model may among other aspects include energy balances, to investigate both the available and requied energies [27].

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