Numerical study of point-to-plane streamer discharge in CF₃I

Xuewen Li∗
Experiment Center of basic course, Shanghai Maritime University, Shanghai 200135, China
E-mail: xwli@shmtu.edu.cn

Abstract. 1D simulation of streamer discharge formation and propagation for a non-uniform electric field (point-to-plane geometry) in CF₃I at atmosphere is presented. Results show Streamer discharge of CF₃I including the phase of electron avalanche and the phase of streamer. The total formative time of streamer discharge in CF₃I is about 2.2 ns, which the first 0.6 ns is taken up with the avalanche development travelling a distance of 0.078 cm from cathode, and the next 1.6 ns by streamer development. Space charge and Photo-ionization have a great influence on the development of gas streamer discharge.

1. Introduction
Sulfur hexafluoride (SF₆) has been widely used as an HV insulating medium, and is also known as a remarkable green house gas, so the research on alternative gas of SF₆ gradually becomes to be a hotspot. Trifluoriodomethane (CF₃I) has been found recently to be a potential high voltage insulator [1]. The GWP of CF₃I is lessen than that of CO₂ (GWP=1), and its lifetime in the atmosphere is estimated to be less than two days, thereby CF₃I ensuring does not deplete the ozone layer, but the insulated strength of pure CF₃I in uniform field is 1.2 multiples above SF₆.

Streamers are ionizing waves moving in a very narrow channel towards either the cathode or anode. To understand insulating property of CF₃I, it is important to study the basic mechanism on streamer discharge of CF₃I. However, recent investigations on gas streamer discharge have largely focused on N₂, SF₆ and air. C. Montijin studied negative streamer discharge of N₂ by means of the minimal streamer model [2]. R. Morrow applied one-dimensional FCT to simulate streamer discharge in SF₆ [3]. Yu. V. Yurgelenas adopted Two-dimensional high-resolution schemes to streamer discharge of air [4]. Furthermore, it is primary stage for streamer discharge of CF₃I.

In this work, under the condition of non-uniform field, the simulation of 1D streamer discharges of CF₃I at atmosphere, positive ion, negative ion and electrons are described by one-dimension particles continuity equation, and coupling with Poisson's equation using Cartesian-coordinates,. Particles continuity equations are solved by a finite-difference flux corrected transport (FCT) technique and finite difference method is adopted to solve Poisson’s equation. Ionization, attachment, diffusion and photo-ionization are considered during the streamer discharge model.

∗ To whom any correspondence should be addressed.
2. Model for a streamer discharge

2.1. Model formulation

The one-dimensional continues equation for electrons and ions can be described as

\[ \frac{\partial N_e}{\partial t} + \frac{\partial (N_e \bar{v}_e)}{\partial x} = D_e \frac{\partial^2 N_e}{\partial x^2} = (\alpha - \eta) N_e |\bar{v}_e| + S_{ph} \]  

(2)

\[ \frac{\partial N_p}{\partial t} + \frac{\partial (N_p \bar{v}_p)}{\partial x} = \mu_e \frac{\partial N_e}{\partial x} \]  

(3)

\[ \frac{\partial N_a}{\partial t} + \frac{\partial (N_a \bar{v}_a)}{\partial x} = \eta N_e |\bar{v}_e| \]  

(4)

Where \( N_p, N_e, N_a \) denote the electrons, positive-ion and negative-ion densities respectively, \( \bar{v}_e, \bar{v}_p, \bar{v}_a \) are the electrons, positive-ion, negative-ion drift velocities respectively, \( D_e \) is electron diffusion coefficient, \( \mu_e \) is mobility of electrons, \( S_{ph} \) is source term of photo-ionization. The symbols \( \alpha, \eta \) denote the ionization, attachment coefficients respectively.

The electric field \( E_{chg} \) due to the space charge is determined by coupled with Poisson’s equation:

\[ \text{div}(\bar{E}_{chg}) = -\frac{e}{\varepsilon_0} (N_p - N_a - N_e) \]  

(5)

Where \( e \) is electron charge, and \( \varepsilon_0 \) is dielectric permittivity of air. Because Laplacian field \( \bar{E}_L \) can be calculated according to structure of electrodes, so the total electric field \( \bar{E} \) is vector sum of \( \bar{E}_L \) and \( \bar{E}_{chg} \).

\[ \bar{E} = \bar{E}_{chg} + \bar{E}_L \]  

(6)

2.2. gas discharge parameters of CF3I

J de Urquijo applied polynomial expression to fitting discharge parameter of CF3I such as ionization coefficient, attachment coefficient etc as follows [5].

\[ \text{Parameter} = a + b(E/N) + c(E/N)^2 + d(E/N)^3 \]  

(7)

Where \( E \) is magnitude of total electrical field, \( E/N \) represents the local reduced electric field, \( N \) is neutral gas number density, and \( a, b, c, d \) are fitting constants for CF3I data. The unit of local reduced electric field \( E/N \) is Td (\( 1 \text{Td}=10^{-17} \text{ V cm}^2 \)).

![Figure 1. fitting ionization, attachment coefficient and effective ionization coefficient of CF3I.](image-url)
As is shown in figure 1, the fitting discharge parameters of CF3I according to formula (7) are applied to streamer discharge model, and detailed model of photo-ionization is obtained from document [6-7].

2.3. A point-to-plane geometry and initial condition

![Figure 2](image)

Figure 2. shows the structure of a point-plane electrode.

In figure 2, the discharge gap with a length of \( d = 0.24 \) cm between a hyperbolic cathode and plain anode was considered. A reference point of the Cartesian coordinates system was located the anode \( (x=0) \), the x-axis was directed toward cathode \( (x=0.24 \) cm). The Laplacian field \( E_L(x) \) is calculated by the formula [8].

\[
E_L(x) = \frac{2V}{\rho + 2(d-x)\ln[(\rho + 2d)/\rho]} \tag{8}
\]

Where \( d=0.24 \) cm, \( \rho \) is the radius of curvature of the electrode tip (\( \rho=500\mu m \)). The voltage on cathode was kept constant and \( V= -29 \) kV. Initial electrons which are near the cathode have a Gaussian distribution as follows

\[
n_e(x) \bigg|_{t=0} = n_0 \exp\left(-\frac{(x-x_0)^2}{\delta_x^2}\right) \tag{9}
\]

Where \( n_0 = 10^9 \) / cm\(^3\), \( \delta_x = 0.01cm \), and \( x_0 = 0.22cm \).

3. Results and discussion

Results are presented for the development of streamer from the negative point of a point-plane gap in CF3I at atmosphere. The calculation is initiated by electrons of a Gaussian distribution released 0.02 cm from the cathode at \( t = 0 \). These electrons move rapidly into high-field region near the cathode tip, ionization neutral gas and producing an increase in the numbers of electrons, forming the initial avalanche. With the rise of electron numbers, a rise in the external circuit current to a maximum of 0.1 mA appeared, shown in figure 3 at \( t = 1.5 \) ns. When the electrons reach the anode and they are absorbed, and then the current falls. Streamer discharge includes phase of streamer formation and phase of propagation in streamer discharge.

The time of initial streamer formation is about 0.6 ns and the avalanche travelling a distance 0.078 cm from cathode according to figure 3-4. The space charge density has risen, and space charge effect has a little influence on electric field at \( t = 0.6 \) ns.
The time of streamer propagation is about 1.6 ns according to figure 5-7. From figure 5, the peak electron density is $5 \times 10^{13}$ cm$^{-3}$, but falls to $1.5 \times 10^{13}$ cm$^{-3}$ along the streamer discharge channel. It may be attributed to the following reasons: First is that negative ions formation from electron attachment. The second is that electrons drift to the anode. Last, the magnitude of electric field decreases along the axis, and that leads to reducing the value of effective ionization coefficient.
As is shown in figure 6, the peak negative net charge density in streamer front varies from \(-1.1 \times 10^{13} \) cm\(^{-3}\), to \(-2.5 \times 10^{13} \) cm\(^{-3}\), but the positive net charge density behind the streamer remains relatively unchanged. With the increase of negative net charge in streamer front, figure 7 shows electric field of streamer front enhanced. Photo-ionization can increase the numbers of electrons, and make space charge of streamer front rise. The electric field between electrodes is distorted by space charge, and further accelerates electrons moving toward anode. Because critical electric field of CF\(_3\)I is equal to 437 Td at which \(\alpha = \eta\). So the numbers of electrons should increase in the streamer discharge region (if \(\alpha > \eta\)). Streamer discharge of CF\(_3\)I can develop from cathode to anode without photo-ionization, but the numbers of electron increase less than that with photo-ionization.

The results of laboratory experiment obtained by Meek show that the streamer advances with a nearly constant velocity except just after starting from one electrode and just before arriving at another electrode. By the recording position of streamer head at different instants of time, the streamer propagation velocity can be determined as

\[
V_o = \frac{\Delta x}{\Delta t}
\]

(10)

Where \(\Delta x\) is the distance adjacent streamer front, and \(\Delta t\) is time of streamer propagation. The position of streamer front can be decided from net charge position coordinates in figure 6. The velocity of streamer front is \(1.21 \times 10^8\) cm s\(^{-1}\) according to equation (10).
4. Conclusions
Some conclusions derived from the calculation results are as follows:

(1) Streamer discharge includes the phase of streamer formation and the phase of propagation. Space charges have a great influence on electric field between electrodes during the period streamer phase.

(2) Though anode-directed streamer can propagate without photo-ionization, it plays an important role in streamer discharge.

(3) Predicted streamer front velocity of $1.21 \times 10^8$ cm s$^{-1}$ is in fair agreement with experimental results.

References
[1] Hiroyuki T, Shigeyasu M and Kunihiko H 2006 Electr. Eng. Jpn. 157 1
[2] Montijn C, Hundsdorfer W, Ebert U 2006 Comput. Phys. 219 1
[3] Morrow R 1981 Comput. Phys. 43 1
[4] Yurgelenas Yu V 2010 Comput Math & Math Phys. 50 1350
[5] Urquijo J de, Juarez A M, Basurto E and Hernandez-Avila J L 2007 Appl. Phys. 40 2205
[6] Kimura M and Nakamura Y 2010 Appl. Phys. 43 1452
[7] Morrow R 1987 Phys. Rev. A. 35 1778
[8] Potamianou S, Spyrou N and Loiseau J-F Appl. Phys. 35 1373