ELECTRON SWARM PARAMETERS IN BINARY GAS MIXTURES OF CF₃I WITH Xe, He, N₂ AND CO₂ FROM BOLTZMANN EQUATION ANALYSIS


Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, 200030, China
*email of corresponding author: dmxiao@sjtu.edu.cn

ABSTRACT

The present paper investigated the insulation characteristics of gas mixtures containing CF₃I as an alternative to SF₆ from the point of view of electron swarm parameters. The density-normalized effective ionization coefficients and electron drift velocities are calculated for the gas mixtures of CF₃I with Xe, He, N₂ and CO₂, by solving the Boltzmann equation in the condition of steady-state Townsend (SST) experiment. The overall range of the density-normalized electric field E/N is from 200 to 800 Td (1 Td = 10⁻¹⁷ Vcm²). From the variation curve of the effective ionization coefficients with the CF₃I mixture ratio, the limiting field strength for which the ionization exactly balances the electron attachment is determined. The calculated results are valid for theoretical analysis of the insulation performance of CF₃I and its gas mixtures as replacement of SF₆. Additionally, the global warming potential (GWP) is also taken into account to evaluate the possibility of applying in gas insulation of power equipment.

1. INTRODUCTION

Because of its high dielectric strength and outstanding interruption performance, sulphur hexafluoride (SF₆) has been widely used as a gaseous insulating medium and an arc quenching medium in the field of high voltage engineering and electrical power applications. However, SF₆ is a strong greenhouse gas with a very high GWP which is 23900 times greater than that of SF₆ over 100-year time period. Consequently, SF₆ has been listed as one of the six principal greenhouse gases of concern according to the Kyoto protocol. In a short term, the gas mixtures of SF₆ with environment friendly gases can reduce the adverse impact on environment, but the lifetime of SF₆ is estimated to be as long as 3200 years because of its chemical inertness and thermal stability, which means that all of the SF₆ that has ever been or will be produced will eventually end up in the atmosphere [2]. The long-term solution to the SF₆ greenhouse problem is to replace SF₆ with an acceptable non-greenhouse gas as the insulating medium.

After decades of exploration and research, there is still no perfect gas to substitute SF₆ with fully consideration of the insulation strength, arcing performance, chemical stability and liquefied temperature. Most of perfluorocarbon (PFC) and hydrofluorocarbons (HFC) which have higher insulation ability than, or comparable to SF₆ also present high GWP or high boiling point, such as c-C₄F₈, n-C₄F₁₀, CF₃SF₅. However, if we use the environment friendly gas such as N₂ and CO₂ to replace SF₆, the size of the insulating equipment would have to be increased since the dielectric strength of these fluorine-free gases is substantially smaller than that of SF₆. Recently, trifluoriodomethane (CF₃I) has been found to be a potential high voltage insulator.

<table>
<thead>
<tr>
<th>Relative molecular mass</th>
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<tr>
<td>Melting point (°C)</td>
<td>-110</td>
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<tr>
<td>Boiling point (°C)</td>
<td>-22.5</td>
</tr>
<tr>
<td>Liquid density (g/cm³)</td>
<td>20°C, 1400</td>
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<td>Critical temperature (°C)</td>
<td>122</td>
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<td>Critical pressure (MPa)</td>
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<td>C-I bond dissociation energy</td>
<td>226.1 kJ/mol</td>
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<tr>
<td>GWP</td>
<td>≤ 5</td>
</tr>
<tr>
<td>ODP</td>
<td>≤ 0.0001</td>
</tr>
<tr>
<td>flammability</td>
<td>non</td>
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Tab. 1: Mainly physical and environmental properties of CF₃I
As shown in Table 1, CF$_3$I is colourless and non-flammable. From the environmental point of view, CF$_3$I presents a weak GWP of 1–5 against approximately 23900 for SF$_6$. Due to the weak chemical bond C-I, the overall atmospheric lifetime of CF$_3$I is very short (at most a few days), which greatly limits its transport to the stratosphere when released at the surface. It has been reported in that the steady-state ozone depletion potential (ODP) of CF$_3$I for surface releases is less than 0.0001. Thus, CF$_3$I is considered as a low environmental impact gas. However, CF$_3$I has a high boiling point -22.5°C [3]. The application of CF$_3$I for insulation inevitably needs it to be mixed with some ordinary gases. The buffer gas composing the greater portion can efficiently decrease the boiling point of the mixture.

In this paper, the density-normalized effective ionization coefficients and electron drift velocities in mixture compositions CF$_3$I–xY, with x = 0-100%, and where Y denotes Xe, He, N$_2$ or CO$_2$ gas, are investigated by solving the electron Boltzmann equation for a steady-state Townsend discharge. The range of the overall density-normalized electric field strength $E/N$ is from 200 to 800 Td. Values of $(E/N)_{\text{lim}}$ with which the ionization exactly balances the electron attachment are deduced from the curves of $(\alpha - \eta)/N$.

2. THEORETIC FRAMEWORK

The numerical method used for solving the Boltzmann equation has been described in detail by the present authors in Ref. [4]. The electron collision cross sections for CF$_3$I are taken from Ref. [5], which have been confirmed to be capable of predicting the experimental limiting $E/N$ values of CF$_3$I–N$_2$ mixtures accurately. While for the companion gas, we use the collisional data of Xe [6], He [7], N$_2$ [8] and CO$_2$ [9] as the initial set.

3. RESULTS AND DISCUSSIONS

Figure 1 shows the density-normalized effective ionization coefficient $(\alpha - \eta)/N$ for different mixture compositions in CF$_3$I–Xe, as a function of the reduced electric field $E/N$. In present work, the electron energy share between the primary and secondary electrons after an ionizing collision is assumed to be 0.5, which means the newly released electron shares half of the primary electron’s energy after the ionization scattering. The results indicate that the values of $(\alpha - \eta)/N$ increase with increasing $E/N$ values, moreover, at a given $E/N$ value, reduce with increasing CF$_3$I content in the mixture. Figure 2 gives the electron drift velocities $V_{e}$, calculated in this work for CF$_3$I–Xe mixtures as a function of the $E/N$. It can be clearly observed that the electron drift velocity displays a quick trend to decrease as the CF$_3$I content increases, especially in the higher $E/N$ range.
Fig. 4: The electron drift velocities in CF$_3$I and He mixtures as a function of E/N at different CF$_3$I gas mixture ratio k(%).

Fig. 5: The density-normalized effective ionization coefficients of CF$_3$I and N$_2$ mixtures as a function of E/N at different CF$_3$I gas mixture ratio k(%).

Fig. 6: The electron drift velocities in CF$_3$I and N$_2$ mixtures as a function of E/N at different CF$_3$I gas mixture ratio k(%).

Fig. 7: The density-normalized effective ionization coefficients of CF$_3$I and CO$_2$ mixtures as a function of E/N at different CF$_3$I gas mixture ratio k(%).

Fig. 8: The electron drift velocities in CF$_3$I and CO$_2$ mixtures as a function of E/N at different CF$_3$I gas mixture ratio k(%).

Figures 3 and 4 show the predicted results for $(\alpha - \eta)/N$ and $V_e$ obtained in CF$_3$I–He mixtures, calculated for CF$_3$I percentages between 25% and 100%. The effective ionization coefficients also display the similar variation trend as observed in CF$_3$I gas mixtures with Xe. Of particular interest is the trend of $(\alpha - \eta)/N$ for higher E/N with respect to the values of $\alpha/N$ for pure He, where the effective ionization coefficients of gas mixtures are still higher than that of pure He even the severe process of attachment occurred with the composing of CF$_3$I. This phenomenon has also been observed in CF$_3$I and N$_2$ gas mixture and may be ascribed to the fact that the ionization potential of CF$_3$I is far more lower (10.23 eV) than that of He (24.6 eV) [10]. The electron drift velocity decrease dramatically as the CF$_3$I content increases.

As regards the electron swarm parameters of CF$_3$I gas mixtures with N$_2$ and CO$_2$, the present authors have detailed discussed in Ref. [11], hence we directly display the results in this section. Figures 5 to 8 show our calculated results obtained in CF$_3$I-N$_2$ and CF$_3$I-CO$_2$ gas mixtures for $(\alpha - \eta)/N$ and $V_e$, respectively.

From the variation of the effective ionization coefficients curves, we can deduce the values of the limiting field strength $(E/N)_{lim}$, i.e. $(\alpha - \eta)/N=0$, for gas mixtures of CF$_3$I with Xe, He, N$_2$ and CO$_2$ at different gas content. Figure 9 shows the $(E/N)_{lim}$ as a function of the CF$_3$I gas percentage. It is seen that the values of $(E/N)_{lim}$ are larger in CF$_3$I-N$_2$ than in the rest gas combinations for the CF$_3$I gas content variation from 20% to 90%, especially for small concentrations of CF$_3$I in the mixtures. However, the increase of CF$_3$I percentage leads to the difference among the four decreases gradually. The main reason for this
behavior may stem on the dominated influence of CF$_3$I on the values for the effective ionization coefficients in the gas mixtures. It reveals that for CF$_3$I concentrations in the gas mixtures of CF$_3$I with N$_2$, CO$_2$ and Xe lower than 70%, the insulation strength of SF$_6$ is superior, but for above this limit, the positions are reversed. Likewise, as judged from these swarm properties, the gas mixtures of CF$_3$I with He can also achieve the same insulation level to that of pure SF$_6$ when the gas content is larger than a certain value.

![Graph](image)

**Fig. 9**: The limiting fields $(E/N)_{lim}$ as a function of CF$_3$I gas content $k$.

### 4. CONCLUSIONS

In this paper, we use the Boltzmann equation method to calculate the density-normalized effective ionization coefficients and electron drift velocities in CF$_3$I gas mixtures with Xe, He, N$_2$, and CO$_2$ for the range of $E/N$ from 200 to 800 Td. It is shown that the two-term expansion of the Boltzmann equation is valid for deducing the electron swarm parameters of CF$_3$I and its gas mixtures. Gas mixtures with 70% CF$_3$I present a very similar dielectric strength to that of SF$_6$ and might be a good candidate to replace SF$_6$ with the advantages of comparable insulation strength and non-environmental destruction. Owing to the scarce number of theoretical analyses in mixtures of CF$_3$I with a buffer gas the present data is justified for the purposes of discharge modeling. Future, more research works should be carried out on the discharge performance of the gas mixtures under different electric field and by-products produced after dielectric breakdown.

### 5. ACKNOWLEDGEMENT

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### REFERENCES


