The effective ionization coefficients and electron drift velocities in gas mixtures of CF_3I with N_2 and CO_2 obtained from Boltzmann equation analysis*

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The electron swarm parameters including the density-normalized effective ionization coefficients $(\alpha-\eta)/N$ and the electron drift velocities V_e are calculated for a gas mixture of CF_3I with N_2 and CO_2 by solving the Boltzmann equation in the condition of a steady-state Townsend (SST) experiment. The overall density-reduced electric field strength is from 100 Td to 1000 Td (1 Td $= 10^{-17}$ V·cm^2), while the CF_3I content k in the gas mixture can be varied over the range from 0% to 100%. From the variation of $(\alpha-\eta)/N$ with the CF_3I mixture ratio k, the limiting field strength $(E/N)_{\rm lim}$ for each CF_3I concentration is derived. It is found that for the mixtures with 70% CF_3I, the values of $(E/N)_{\rm lim}$ are essentially the same as that for pure SF_6. Additionally, the global warming potential (GWP) and the liquefaction temperature of the gas mixtures are also taken into account to evaluate the possibility of application in the gas insulation of power equipment.

Keywords: effective ionization coefficient, electron drift velocity, insulation characteristics, CF_3I gas mixtures

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1. Introduction

Because of its high dielectric strength and outstanding interruption performance, sulfur hexafluoride (SF_6) 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, apprehension has been arising about the fact that SF_6 was identified as a principal greenhouse gas in the Kyoto Protocol. In the short term, gas mixtures of SF_6 with environmentally friendly gases can reduce the adverse impact on the environment, but the lifetime of SF_6 is estimated to be as long as 3200 years because of its chemical inertness and thermal stability, which means that all of the SF_6 that has ever been or will be produced will eventually end up in the atmosphere.[1] The long-term solution to the SF_6 greenhouse problem is to replace SF_6 with an acceptable non-greenhouse gas as the insulating medium.

Recently, trifluoroiodomethane (CF_3I) has been found to be a potential high voltage insulator, both on its own and mixed with N_2 and CO_2.[2,3] Generally, CF_3I is colorless and nonflammable.[4] From an environmental point of view, CF_3I presents a weak global warming potential (GWP) of 1–5 against approximately 23900 for SF_6.[5] Due to the weak chemical bond C–I, the overall atmospheric lifetime of CF_3I is very short (at most a few days), which greatly limits its transport to the stratosphere when released at the surface.[4] It has been reported in Ref. [6] that the steady-state ozone depletion potential (ODP) of CF_3I for surface releases is less than 0.0001. Thus, CF_3I is considered as a low environmental impact gas and is attracting widespread attention for comprehensive study. However, CF_3I has a high boiling point -22.5 °C, as reported in Ref. [7]. The application of CF_3I for insulation inevitably needs it to be mixed with with ordinary gases, such as N_2, CO_2, and air, the buffer gas composing the greater portion can efficiently decrease the boiling point of the mixture.

With this aim, swarm parameters in the gas mixture of CF_3I with N_2 have been recently measured by de Urquijo *et al.*[8] with a pulse Townsend (PT) technique. For CF_3I/N_2 mixture with 70% CF_3I, the limiting field strength $(E/N)_{\rm lim}$ was found to be essentially the same as that for pure SF_6, which means that the CF_3I mixture with N_2 would be a viable gaseous dielectric as an alterative for SF_6. Furthermore, Katagiri *et al.*[9] investigated the breakdown voltage characteristics of CF_3I gas and its mixture with CO_2 using a standard lightning impulse voltage. The results indicated that the insulation performance of CF_3I is 1.2 times better than that of pure SF_6. On the other hand, 30%–70% CF_3I/CO_2 can achieve a dielectric strength equaling about 0.75–0.80 times of that of SF_6. Recent studies by Cressault *et al.*[5] discussed the transport properties of CF_3I thermal plasmas mixed with CO_2, air, or N_2 from the thermodynamic point of view. However, there are few studies on deriving the electron swarm parameters from Boltzmann equation analysis or Monte–Carlo simulation for CF_3I gas mixtures. Due to the potential importance of CF_3I and its binary mixtures as replacements of SF_6, more theoretical studies are needed.

In the present paper, the effective ionization coefficients

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and the electron drift velocities in mixtures of CF_3I with N_2 and CO_2 are investigated through solving the Boltzmann equation for a steady-state Townsend (SST) discharge. The range covered is 100–1000 Td, while the CF_3I content in the gas mixtures is varied over the range 0–100%. Values of $(E/N)_{\rm lim}$ with which the ionization exactly balances the electron attachment are deduced from the curves of $(\alpha-\eta)/N$ and compared with those of SF_6/N_2 gas mixtures. The calculated results show that gas mixtures of CF_3I with N_2 and CO_2 have reasonably good insulation strengths under an uniform equilibrium condition, and the insulation characteristics are even superior to that of SF_6 when the CF_3I content is larger than 70%. Moreover, we will discuss the liquefaction temperatures of the gas mixtures and analyze the possibility of application in the gas insulation of power equipment.

2. Boltzmann equation method

The numerical method used for solving the Boltzmann equation has been described in detail by the present authors in Ref. [10]. A brief introduction is given below.

In the SST experiment under an equilibrium condition, the Boltzmann equation can be given as

$$(\alpha-\eta)v\cos\theta f+a\left(\cos\theta\frac{\partial f}{\partial v}-\frac{\sin\theta}{v}\frac{\partial f}{\partial\theta}\right)=C\Big[f(r,v,t)\Big], \quad (1)$$

where f is the electron velocity distribution function, v is the electron velocity, θ is the angle between the velocity and the inverse field direction, α and η are the ionization and the attachment coefficients, respectively, $a=eE/m$ is the acceleration in the electric field, r is the electron position, and $C[f(r,v,t)]$ is the general collision operator including elastic and inelastic collisions.

The two-term expansion of the velocity distribution function f in spherical harmonics of $\cos\theta$, because of the axial symmetry of the problem, becomes an expansion in the zero-order Legendre polynomials $\mathrm{P}_j(\cos\theta)$. Thus f takes the form[11]

$$f(v,\theta)=f_0(v)+f_1(v)\cos\theta, \quad (2)$$

where f_0 and f_1 represent the isotropic and the anisotropic parts of f, respectively. Substituting Eq. (3) into Eq. (2), we can get[12]

$$\begin{aligned}&\frac{1}{3}(\alpha-\eta)vf_1+\frac{1}{3}\frac{eE}{mv^2}\frac{\partial}{\partial v}(v^2f_1)\\ =\;&\frac{m}{M}\frac{N}{v^2}\frac{\partial}{\partial v}(v^4Q_{\rm m}f_0)+\sum_j N\frac{v_j^2}{v}Q_{\rm e}(v_j)f_0(v_j)\\ &+\frac{N}{\Delta}\frac{v_{i,1}^2}{v}Q_{\rm i}(v_{i,1})f_0(v_{i,1})+\frac{N}{1-\Delta}\frac{v_{i,2}^2}{v}Q_{\rm i}(v_{i,2})f_0(v_{i,2})\\ &-Nv\Big(\sum_j Q_{\rm e}+Q_{\rm i}+Q_{\rm a}\Big)f_0, \quad (3)\end{aligned}$$

$$(\alpha-\eta)vf_0+\frac{eE}{m}\frac{\partial f_0}{\partial v}=-Nv\Big(Q_{\rm m}+\sum_j Q_{\rm e}+Q_{\rm i}+Q_{\rm a}\Big)f_1. \quad (4)$$

The $f_0(v)$ is normalized as

$$\int_0^\infty 4\pi v^2 f_0(v)\,{\rm d}v=1. \quad (5)$$

Here, e/m represents the electron charge mass ratio, M is the molecular mass, N is the gas density, and Δ is a parameter specifying the share of energy between the primary and the secondary electrons after the ionizing collision. The $Q_{\rm m}$, $Q_{\rm e}$, $Q_{\rm i}$, and $Q_{\rm a}$ denote the electron cross sections of momentum transfer, excitation, ionization, and attachment, respectively. The excitation cross section $Q_{\rm e}$ contains not only the electronic but also the vibrational excitation cross sections. Especially, if there is a dissociation process to produce neutral fragments, the dissociation cross section should also be included into the excitation cross section set. The numerical method, called backward prolongation and relaxation with energy balance check, is used to solve Eqs. (3) and (4) after we transform the variable from velocity v to energy ε by the relation $\varepsilon=mv^2/2$.

(i) An initial value of $(\alpha-\eta)$ is assumed and submitted to Eqs. (3) and (4), then f_0 and f_1 are obtained.

(ii) The ionization coefficient α and the attachment coefficient η are calculated by

$$\alpha=3N\int_0^\infty Q_{\rm i}(\varepsilon)\varepsilon f_0(\varepsilon)\,{\rm d}\varepsilon\left[\int_0^\infty \varepsilon f_1(\varepsilon)\,{\rm d}\varepsilon\right]^{-1}, \quad (6)$$

$$\eta=3N\int_0^\infty Q_{\rm a}(\varepsilon)\varepsilon f_0(\varepsilon)\,{\rm d}\varepsilon\left[\int_0^\infty \varepsilon f_1(\varepsilon)\,{\rm d}\varepsilon\right]^{-1}. \quad (7)$$

(iii) The $(\alpha-\eta)$ value is submitted into the equations again, and f_0 and f_1 are modified.

(iv) Repeat the above procedures until a sufficient convergence is achieved for the effective ionization coefficient. The relaxation is terminated when $|(\overline{\alpha}_n-\overline{\alpha}_{n-1})/\overline{\alpha}_n|\leq 10^{-4}$, where $\overline{\alpha}_n$ is the n-th value for $(\alpha-\eta)$.

(v) After f_0 and f_1 are finally determined, the electron swarm parameters including the drift velocity $V_{\rm e}$ and the mean energy $\overline{\varepsilon}$ can be calculated by

$$V_{\rm e}=-\frac{eE}{3N}\sqrt{\frac{2}{m}}\int_0^\infty\frac{\varepsilon}{Q_{\rm m}^{\rm T}}\frac{{\rm d}f_0(\varepsilon)}{{\rm d}\varepsilon}\,{\rm d}\varepsilon, \quad (8)$$

$$\overline{\varepsilon}=\int_0^\infty \varepsilon^{3/2}f_0(\varepsilon)\,{\rm d}\varepsilon, \quad (9)$$

where $Q_{\rm m}^{\rm T}=Q_{\rm m}+\sum_j Q_{\rm e}+Q_{\rm i}+Q_{\rm a}$ denotes the total effective collision cross section for momentum transfer. For a gas mixture, $Q_{\rm m}^{\rm T}=\sum_n k_n Q_{{\rm m},n}^{\rm T}$, where k_n is the admixture ratio of each component.

The electron collision cross sections for CF_3I are taken from Ref. [13], which have been confirmed to be capable of predicting the experimental limiting E/N values of CF_3I–N_2 mixtures accurately. While for the companion gas, we use the collisional data of N_2 determined by Phelps and Pitchford[14]

and that of CO_2 summarized by Itikawa[15] as the initial set. Figure 1 shows the cross sections for the electron collision with CF_3I used in this paper.

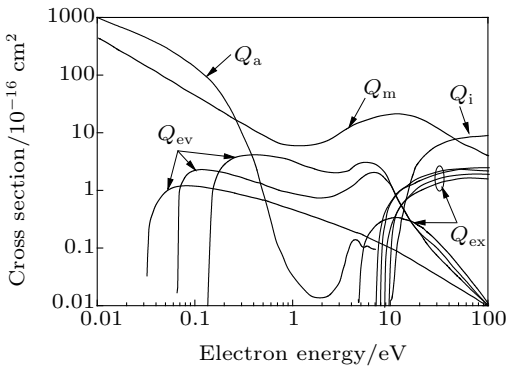


Fig. 1. Cross sections of CF_3I: momentum transfer cross section Q_m, electronic excitation cross section Q_{ex}, vibrational excitation cross section Q_{ev}, ionization cross section Q_i, attachment cross section Q_a.[13]

3. Calculation results and discussion

In this work, the gas number density is $N = 3.29 \times 10^{22}$ m^{-3} in the pressure of 1 Torr at 20 °C. The three-body collisions are neglected, and the Coulomb interaction between charged particles is also out of consideration as a result of the low gas pressure and the low ionization degree.[16] Yousfi *et al.*[17] pointed out that the value of attachment is sensitive to the energy partition Δ after ionization. A value of 0.5 is employed for Δ in the present analysis, which means the newly released electron shares half of the primary electron's energy after the ionization scattering.

3.1. Electron swarm parameters of CF_3I

The numerical solution we obtained for normalized effective ionization coefficient $(\alpha - \eta)/N$ in pure CF_3I is shown in Fig. 2 and compared with the data of experiments[8,18] and Monte–Carlo simulation[13] in the E/N range from 100 Td to 1000 Td. The limiting field strength for CF_3I, which is defined as the value of E/N at which ionization equals attachment, i.e., $(\alpha - \eta)/N = 0$, is approximately equal to 431 Td. This means that the insulation strength of pure CF_3I is 1.19 times that of SF_6, where the $(E/N)_{lim}$ of SF_6 is established to be 361 Td.[1] The values of $(E/N)_{lim}$ for CF_3I were determined by de Urquijo *et al.*[8] and Hasegawa *et al.*[18] from pulse Townsend (PT) and steady-state Townsend (SST) experiments to be 437 Td and 440 Td, respectively. There are slight deviations between the calculated and the measured results, however we believe the deviations are not serious because of the estimated error limits in the present calculations.[19,20]

Figure 3 shows the electron drift velocity V_e in pure CF_3I calculated with the cross sections estimated in the present paper as a function of E/N. The electron drift velocities measured by de Urquijo *et al.*[8] with the PT technique and Hasegawa *et al.*[18] with the arrival-time spectrum (ATS) method are also displayed for comparisons. It is seen that the values calculated in the present analysis are smaller than those determined by the ATS method by 5% for the whole E/N range, however, they agree fairly well with those obtained from the PT experiment and the Monte–Carlo simulation.[13]

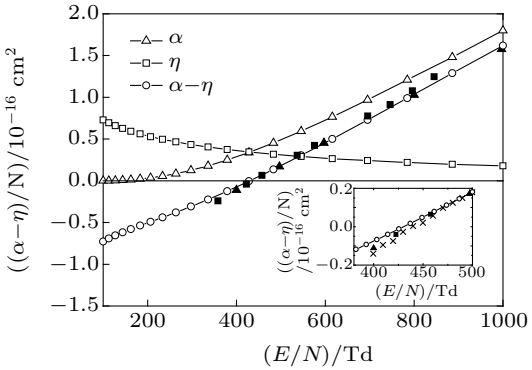


Fig. 2. Effective ionization coefficient $(\alpha - \eta)/N$ of CF_3I as a function of E/N, symbols ■, ×, ▲, and ○ represent results obtained by de Urquijo *et al.* through PT experiment,[8] Hasegawa *et al.* through SST experiment,[18] Kimura and Nakamura through Monte–Carlo simulation,[13] and the present work, respectively.

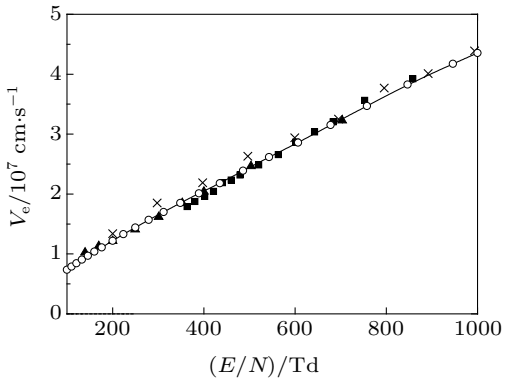


Fig. 3. Electron drift velocity in CF_3I as a function of E/N, symbols ■, ×, ▲, and ○ represent results obtained by de Urquijo *et al.* through PT experiment,[8] Hasegawa *et al.* through SST experiment,[18] Kimura and Nakamura through Monte–Carlo simulation,[13] and the present work, respectively.

Even though the calculated effective ionization coefficient and electron drift velocity in CF_3I are consistent with the experimental data, it is worth emphasizing that the two-term spherical harmonic expansion of the Boltzmann equation poorly represents the highly anisotropic electron distribution.[11] Therefore, the two-term expansion has an insufficiency that it can not give $D_{v\parallel}$ and $D_{v\perp}$ separately, where $D_{v\parallel}$ and $D_{v\perp}$ are the diffusion coefficients parallel and perpendicular to the field direction, respectively.[21] However, in the case of low pressure at 1 Torr, the velocity distribution of the electron is nearly isotropic, and the difference between $D_{v\parallel}$ and $D_{v\perp}$ is sufficiently small.[22] The two-term approximation of the Boltzmann equation is still valid for calculating the corresponding rate and transport coefficients with the advantages of short computing time and considerable accuracy in discharge modelling.[20]

3.2. Effective ionization coefficients and electron drift velocities in mixtures of CF_3I with N_2 and CO_2

The isotropic components of the electron energy distribution functions $f_0(\varepsilon)$ calculated for pure CF_3I, 50% CF_3I/N_2 gas mixture, and pure N_2 at $E/N = 300$ Td with $\Delta = 0.5$ are shown in Fig. 4. As the gas composition changes from pure N_2 to a mixture predominately constituted by CF_3I, the CF_3I molecules present high reactivity for electron attachment, which produces a depletion of the electrons of extremely low energies. The addition of CF_3I into the mixture increases the peak of the energy distributions in the low-energy range, indicating that the number of low energy electrons increases in the swarm, and thus the mean energy should decrease with the increasing CF_3I content in the mixture, which is demonstrated in Fig. 5.

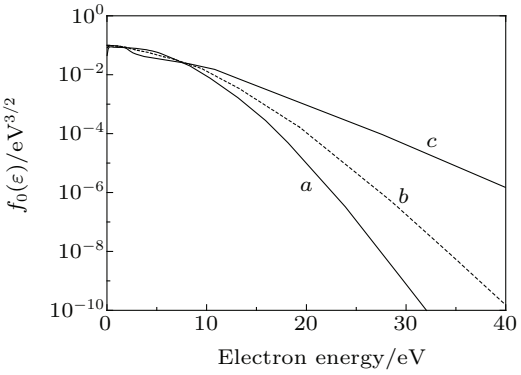


Fig. 4. The isotropic components of the electron energy distribution function $f_0(\varepsilon)$ for $E/N = 300$ Td, $\Delta = 0.5$ in pure CF_3I (curve *a*), 50% N_2–50% CF_3I (curve *b*), and pure N_2 (curve *c*).

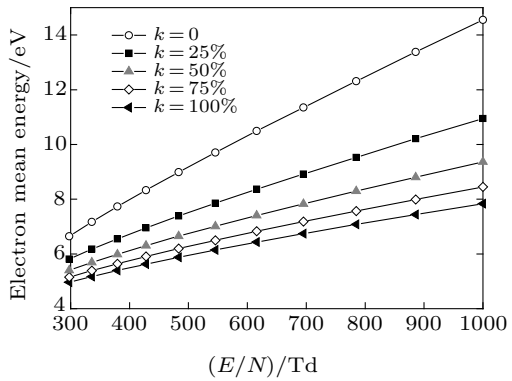


Fig. 5. The electron mean energy in CF_3I and N_2 mixtures as a function of E/N at different CF_3I gas mixture ratio *k*.

The density-normalized effective ionization coefficients $(\alpha - \eta)/N$ calculated in the present analysis for CF_3I and N_2 gas mixtures with 1%, 2%, 5%, 10%, 25%, 50%, and 75% CF_3I as a function of the density-reduced electric field are shown in Fig. 6. The results indicate that $(\alpha - \eta)/N$ increases with the increasing E/N, moreover, at a given value, it reduces with the increasing CF_3I content in the mixture. Of particular interest is the trend of $(\alpha - \eta)/N$ with respect to the value of α/N for pure N_2, where the effective ionization coefficients of gas mixtures are still higher than those of pure N_2 even the severe process of attachment occurs with the composing of CF_3I. This phenomenon has been confirmed through experiment measurements and can be ascribed to the fact that the ionization potential of CF_3I (10.23 eV) is lower [13] than that of N_2 (15.58 eV).[8,14] The recommended $(\alpha - \eta)/N$ values for SF_6 are also shown for comparison.[23]

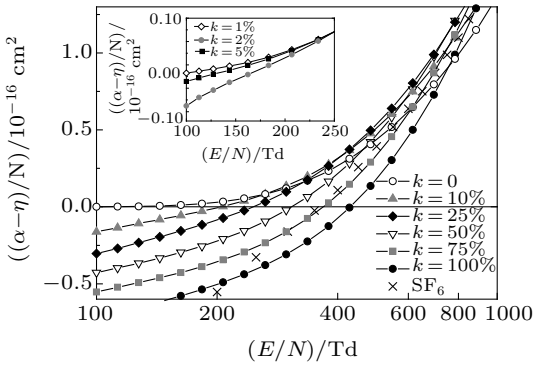


Fig. 6. Density-normalized effective ionization coefficients $(\alpha - \eta)/N$ of CF_3I and N_2 mixtures as a function of E/N at different CF_3I gas mixture ratio *k*. The crosses represent the recommended $(\alpha - \eta)/N$ for SF_6.[23] The inset shows the results for low *k*.

Figure 7 gives the electron drift velocities V_e calculated in this work for pure CF_3I and CF_3I/N_2 mixtures as a function of E/N. It can be clearly observed that the electron drift velocity displays a trend to quickly decrease as the CF_3I content increases. The reasons for the changes in V_e are twofold. First, the effective collision frequencies for momentum transfer in CF_3I and N_2 are differently weighted in Eq. (8) as the composition changes. Second, the most significant changes arise from the modifications on the electron energy distribution function with the addition of the strongly electronegative gas CF_3I. Again, for the sake of comparison, reliable data of this parameter for pure SF_6, the values from Christophorou and Olthoff,[23] are shown for order-of-magnitude comparison with those of CF_3I and CF_3I/N_2 mixtures. Interestingly, the V_e values for 75% CF_3I/N_2 gas mixture overlap with those of SF_6 in the range of from 200 Td to 600 Td.

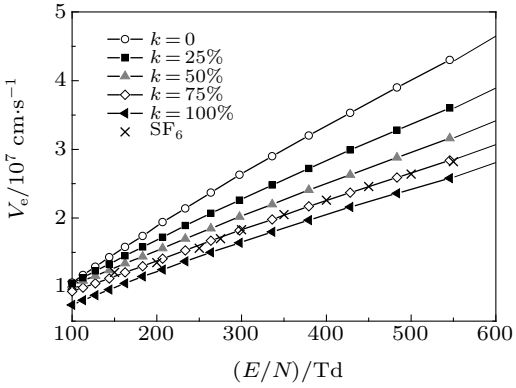


Fig. 7. Electron drift velocities V_e of CF_3I and N_2 mixtures as a function of E/N at different CF_3I gas mixture ratio *k*. The crosses represent the recommended electron drift velocities for SF_6.[23]

Figures 8 and 9 respectively show the predicted results for $(\alpha-\eta)/N$ and obtained in the CF_3I/CO_2 gas mixtures. To the best of our knowledge, the swarm data in CF_3I/CO_2 mixtures are very limited in the literature. The variation trend of $(\alpha-\eta)/N$ in the gas mixtures is similar to that of CF_3I/N_2, i.e., for a fixed E/N, the present $(\alpha-\eta)/N$ data display a fairly uniform trend of decrease as the CF_3I content in the mixture increases. This is a consequence of the increasingly electronegative character of the mixture, regardless of the mixture composition, over the range studied.

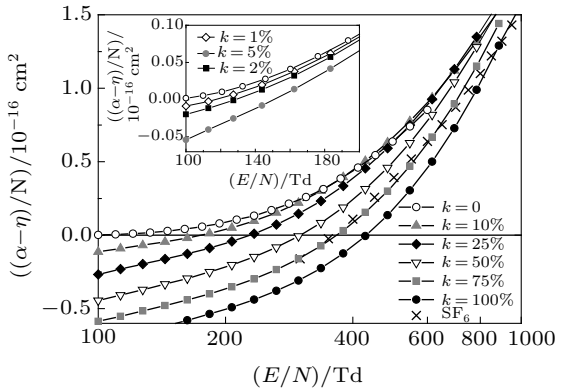


Fig. 8. Density-normalized effective ionization coefficients $(\alpha-\eta)/N$ of CF_3I and CO_2 mixtures as a function of E/N at different CF_3I gas mixture ratio k. The crosses represent the recommended $(\alpha-\eta)/N$ for SF_6.[23] The inset shows the results for low k.

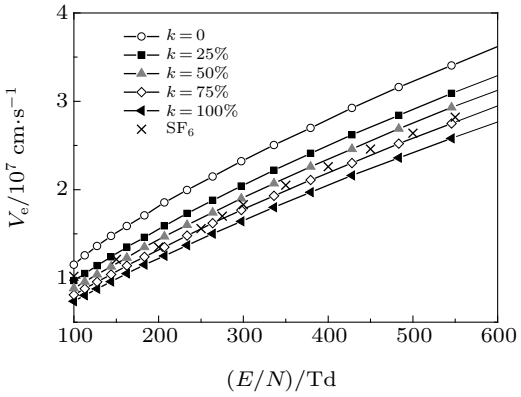


Fig. 9. The electron drift velocity V_e in CF_3I/CO_2 mixtures and SF_6 as a function of E/N at different CF_3I gas mixture ratio k. The crosses represent the recommended electron drift velocities for SF_6.[23]

From the variation of the effective ionization coefficient curves, we can deduce the values of the limiting field strength $(E/N)_{\rm lim}$ for the gas mixtures of CF_3I with N_2 and CO_2. Figure 10 presents $(E/N)_{\rm lim}$ as a function of the percentage of CF_3I in the mixture. It is seen that $(E/N)_{\rm lim}$ of CF_3I/N_2 is higher than that of CF_3I/CO_2 especially for small concentrations ($< 10\%$) of CF_3I in the mixture. However, the increase of CF_3I percentage leads to the difference between the two decreases gradually. The main reason for this behavior may stem from the dominated influence of CF_3I on the effective ionization coefficient in the gas mixture. Because the SF_6/N_2 mixture has been widely used as an important binary gas mixture for power equipments, the critical field strength values for SF_6/N_2 mixtures are also given in Fig. 10 for comparison.[23] It reveals that for CF_3I concentrations in the gas mixtures of CF_3I with N_2 and CO_2 lower than 60%, the SF_6/N_2 mixture is superior, but above this value, the positions are reversed. As a matter of fact, judged from these swarm properties, the 70% gas mixtures of CF_3I with N_2 and CO_2 are even superior to pure SF_6.

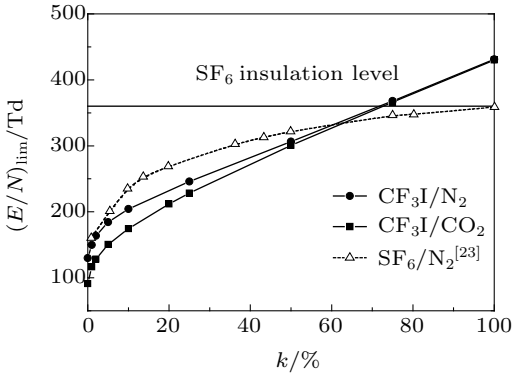


Fig. 10. The limiting fields $(E/N)_{\rm lim}$ as a function of CF_3I or SF_6 gas content k.

3.3. Possibility of applying gas mixtures of CF_3I with N_2 and CO_2 in power equipment

The application of CF_3I for gas insulation is inevitably concerned with the liquefaction temperature. The vapor pressure P_v (MPa) of CF_3I is dependent on the temperature T (K) through the following fitting equation:[7]

$$\lg(P_v/P_c) = (A_1\tau + A_2\tau^{1.25} + A_3\tau^3 + A_4\tau^7)T_c/T, \quad (10)$$

where $\tau = 1 - T/T_c$, $A_1 = -7.19045$, $A_2 = -1.34829$, $A_3 = -1.58035$, $A_4 = -5.46680$, $T_c = 395.05$ K, and $P_c = 3.8617$ MPa. The equation of state for gases (Van der Waals equation) is given as[24]

$$\left(P + \frac{a}{V^2}\right)(V-b) = RT, \quad (11)$$

where P and V are the pressure and the volume of the gas, T is the absolute temperature, R denotes the molar gas constant, and a and b are the Van der Waals constants. For CF_3I, $a = 1.1967$ Pa·(m^3/mol)^2, $b = 1.0626\times10^{-4}$ m^3/mol.

We assume that T_0 is the primary temperature of the gas mixture, P_0 is the primary pressure, T_m is the liquefaction temperature, and P_m is the pressure corresponding to T_m. The state of the gas mixture meets the following equations:

$$\lg(P_m/P_c) = (A_1\tau + A_2\tau^{1.25} + A_3\tau^3 + A_4\tau^7)T_c/T_m, \quad (12)$$

$$\left(kP_m + \frac{a}{V^2}\right)(V-b) = RT_m, \quad (13)$$

$$\left(kP_0 + \frac{a}{V^2}\right)(V-b) = RT_0. \quad (14)$$

Solving the above three equations, we get the liquefaction temperature T_m of the CF_3I/N_2 gas mixture at different pressure, which is presented in Fig. 11.

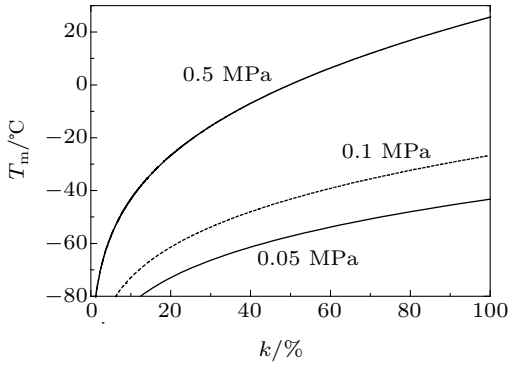


Fig. 11. Relation of the liquefaction temperature of CF_3I/N_2 gas mixture as a function of CF_3I content k at different gas pressure.

Typically, 0.5 MPa of SF_6 is used in gas insulated switchgear (GIS). At 0.5 MPa, the boiling point of 70% CF_3I/N_2 is as high as 12 °C. The result is frustrating for applying the gas mixture in GIS. However, there is still practical value in other gas insulated equipment. Most cubicle type gas insulated switchgears (C-GIS) do not need such a high pressure as the GIS (0.5 MPa). For example, the Siemens cubicle gas-insulated switchgear 8DA11/8DA12 employs 0.05–0.1 MPa of SF_6 as the insulation medium . If we use 70% content of CF_3I/N_2 or CF_3I/CO_2 gas mixture as the insulation medium, the boiling point can decrease to −35 °C at the pressure of 0.1 MPa. This is acceptable for applying the gas mixtures in the high voltage apparatus used in the mid-low latitude regions.

4. Conclusion

In this study, the effective ionization coefficients, the electron drift velocities, and the limiting field strengths in binary CF_3I/N_2 and CF_3I/CO_2 gas mixtures are evaluated by employing a two-term spherical harmonic approximation of the Boltzmann transport equation over the range of E/N from 100 Td to 1000 Td. The calculated results indicate that gas mixtures with 70% CF_3I present a very similar dielectric strength to that of SF_6. Furthermore, the global warming potentials of the gas mixtures are obviously reduced. From the insulation strength point of view, the gas mixtures of CF_3I with N_2 and CO_2 can be potential replacements for SF_6 and SF_6/N_2 in some high voltage apparatus such as C-GIS with the advantages of comparable limiting field strength and lower environmental impact. Admittedly, more research work should be carried out on the chemical, thermal, and current interrupting characteristics of CF_3I, especially for its mixtures, as substitutes for SF_6 in high voltage applications.

References

[1] Christophorou L and Van Brunt R 1995 *IEEE Trans. Dielectr. Electr. Insul.* **2** 952
[2] Nakauchi S, Tosu D, Matsuoka S, Kumada A and Hidaka K 2006 *Proc. 16th Int. Conf. on Gas Discharges and their Applications*, September 11–15, 2006 Xi'an, China, p. 365
[3] Taki M, Maekawa D, Odaka H, Mizoguchi H and Yanabu S 2007 *IEEE Trans. Dielectr. Electr. Insul.* **14** 341
[4] Christophorou L G and Olthoff J K 2000 *J. Phys. Chem. Ref. Data* **29** 553
[5] Cressault Y, Connord V, Hingana H, Teulet P and Gleizes A 2011 *J. Phys. D: Appl. Phys.* **44** 495202
[6] Solomon S, Burkholder J, Ravishankara A and Garcia R 1994 *J. Geophys. Res.* **99** 20929
[7] Duan Y Y, Zhu M S and Han L Z 1996 *Fluid Phase Equilib.* **121** 227
[8] de Urquijo J, Juárez A, Basurto E and Hernández-Ávila J 2007 *J. Phys. D: Appl. Phys.* **40** 2205
[9] Katagiri H, Kasuya H, Mizoguchi H and Yanabu S 2008 *IEEE Trans. Dielectr. Electr. Insul.* **15** 1424
[10] Deng Y K and Xiao D M 2012 *Eur. Phys. J. Appl. Phys.* **57** 20801
[11] Pitchford L and Phelps A 1982 *Phys. Rev. A* **25** 540
[12] Yachi S, Kitamura Y, Kitamori K and Tagashira H 1988 *J. Phys. D: Appl. Phys.* **21** 914
[13] Kimura M and Nakamura Y 2010 *J. Phys. D: Appl. Phys.* **43** 145202
[14] Phelps A and Pitchford L 1985 *Phys. Rev. A* **31** 2932
[15] Itikawa Y 2002 *J. Phys. Chem. Ref. Data* **31** 749
[16] Tagashira H, Sakai Y and Sakamoto S 1977 *J. Phys. D: Appl. Phys.* **10** 1051
[17] Yousfi M, Segur P and Vassiliadis T 1985 *J. Phys. D: Appl. Phys.* **18** 359
[18] Hasegawa H, Shimozuma M and Itoh H 2009 *Appl. Phys. Lett.* **95** 101504
[19] White R, Robson R, Schmidt B and Morrison M 2003 *J. Phys. D: Appl. Phys.* **36** 3125
[20] Pinhão N, Donkó Z, Loffhagen D, Pinheiro M and Richley E 2004 *Plasma Sources Sci. Technol.* **13** 719
[21] Kitamori K, Tagashira H and Sakai Y 1978 *J. Phys. D: Appl. Phys.* **11** 283
[22] Wen C 1989 *Time-resolved Swarm Studies in Gases with Emphasis on Electron Detachment and Ion Conversion* (Ph. D. Thesis) (Netherlands: Eindhoven University of Technology)
[23] Christophorou L and Olthoff J 2000 *J. Phys. Chem. Ref. Data* **29** 267
[24] Poling B, Prausnitz J and John Paul O 2001 *The Properties of Gases and Liquids* (Vol. 5) (New York: McGraw-Hill)