Ionization and Attachment Coefficients in C₄F₇N Gas Measured by the Steady-State Townsend Method

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Abstract: The normalized Townsend first ionization coefficient \( \alpha/N \) and normalized attachment coefficient \( \eta/N \) in pure \( \text{C}_4\text{F}_7\text{N} \) were measured by using the steady-state Townsend (SST) method for a range of reduced electric fields \( E/N \) from 750 to 1150 Td at room temperature \( (20^\circ \text{C}) \). Meanwhile, the effective ionization coefficients are obtained. All SST experimental results show good agreement with pulsed Townsend (PT) experiment results. Comparisons of the critical electric fields of \( \text{C}_4\text{F}_7\text{N} \) with \( \text{SF}_6 \) and other alternative gases such as \( \text{C}_4\text{F}_8 \) and \( \text{CF}_3\text{I} \) indicate that \( \text{C}_4\text{F}_7\text{N} \) has a better insulation performance with a much higher normalized critical electric field at 959.19 Td.

Keywords: \( \text{C}_4\text{F}_7\text{N} \); ionization coefficient; attachment coefficient; critical electric field; steady-state Townsend method; ionization; plasma; gas discharge; high voltage; \( \text{SF}_6 \)

1. Introduction

As is well known, sulfur hexafluoride (\( \text{SF}_6 \)), with a good insulation performance and thermal stability, is widely used as an insulation gas and arc quenching medium in many fields such as high-voltage engineering and electrical power applications [1,2]. Unfortunately, as one of the six greenhouse gases, \( \text{SF}_6 \) has an extremely high global warming potential (GWP₁₀₀) at 23,500 times that of \( \text{CO}_2 \) [3]. Thus, in order to slow down global warming, searching for an environment-friendly insulation gas to reduce the use of \( \text{SF}_6 \) is of great importance.

During the last decades, there has been some research about the discharge characteristics of \( \text{c-C}_4\text{F}_8 \) [4–6] and \( \text{CF}_3\text{I} \) [7–9], which have been thought of as potential alternative gases to \( \text{SF}_6 \). Recently, as another newly potential substitutional insulation gas of \( \text{SF}_6 \), fluoronitriles (\( \text{C}_4\text{F}_7\text{N} \), also known as 3M Novec-4710), which have a GWP value of 2100, have been designed and have attracted great attention [10]. Although \( \text{C}_4\text{F}_7\text{N} \) gas has a good insulation performance, because of its high boiling temperature, it has to be mixed with other buffer gases such as \( \text{CO}_2 \) to adapt to the operating conditions under high gas pressure [11]. Nevertheless, it is worthy to obtain the basic electron swarms of \( \text{C}_4\text{F}_7\text{N} \), such as the ionization coefficient \( \alpha \) and attachment coefficient \( \eta \), which can be used to evaluate the insulation performance of gases [12].
However, it should be noted that there has been less investigation on the ionization coefficients and attachment coefficients in C₄F₇N. It has been reported once that the normalized effective ionization coefficient (\(\alpha/N\)) within a small range of reduced electric fields (per gas density \(N\)) \(E/N\) was obtained with the steady-state Townsend (SST) method by Nechmi et al. [13]. The electron rate and transport coefficients in pure C₄F₇N were obtained with the pulsed Townsend (PT) method by Chachereau et al. [14]. In the present work, both normalized ionization and normalized attachment coefficients, as well as effective ionization coefficients of C₄F₇N, were measured by the SST method, a kind of method which has been widely used to measure these coefficients in different gases like SF₆ [15–17], c-C₄F₈ [4], CF₃I [8], and so on. It should also be noticed that although the SST method has been well developed during the last decades, and the innovation of the method itself may not be high, the experiments using this method to measure and obtain the discharge parameters and evaluate the insulation abilities of new insulation gases are still significant.

2. Experiments

The experiments were carried out on an SST apparatus setup in Wuhan University, which the details have been described in previous work [18,19]. The reliability of this SST apparatus has been verified by experiments on known gases such as SF₆ and N₂, which showed this SST apparatus has great measurement accuracy (<2%) [19]. The theoretical equations used to obtain the experimental results have been introduced as well. Through the update of vacuum-tight gaskets, the background vacuum degree in the ionization chamber can reach ~1.0 × 10⁻³ Pa at room temperature with a leak rate less than 0.10 Pa/h, which can minimize the effect of the pressure change on experimental results. In the present study, the range of reduced electric fields \(E/N\) applied for the SST experiment varied from 750 to 1150 Td (1 Td = 10⁻²¹ Vm²), since the insulation performance of C₄F₇N is much better than SF₆ as reported [13,14]. The purity of C₄F₇N gas (produced by Beijing Yuji Science and Technology Co., Ltd., China) used in the present study was more than 99.6%, and the impurities were mainly air (~0.3%). The gas pressure was 500 Pa at 20 °C. The initial electron current \(I₀\) of the electron avalanche was about 4 pA, and current \(I\) in the nonself-sustained discharge stage was also on the order of picoampere (pA).

3. Results and Discussion

3.1. Ionization and Attachment Coefficients

The normalized ionization coefficient \(\alpha/N\) and the attachment coefficient \(\eta/N\) of C₄F₇N gas for 750 Td < \(E/N\) < 1150 Td were measured respectively. The results were compared to that of SF₆ gas and shown in Figure 1. It was found that with an increasing \(E/N\), the \(\alpha/N\) of C₄F₇N showed a growing trend, while the \(\eta/N\) showed a clear decreasing trend, which were similar to that of SF₆ [3]. Meanwhile, compared to SF₆ gas, it was apparent that the values of \(\eta/N\) in C₄F₇N were much higher than that of SF₆ for the same \(E/N\), which could be explained with the attachment cross-sections in different gases. The higher the attachment cross section is, the stronger the ability of electron attachment is. The total attachment cross-sections of C₄F₇N [14], SF₆ [9], and other gases [9,20] have been compared and plotted in Figure 2. As reported [14], the total attachment cross-section in C₄F₇N was larger than that of SF₆ above 0.1 eV, while the values of \(\alpha/N\) were a little bit smaller than that of SF₆ when \(E/N\) < 900 Td. When \(E/N\) > 900 Td, the values of \(\alpha/N\) in C₄F₇N were a little bit higher than that of SF₆. Therefore, for C₄F₇N and SF₆ with similar values of ionization coefficients, C₄F₇N had a better insulation performance due to the much higher attachment coefficient than that of SF₆.
was much larger than that of SST, which may be caused by the different experimental principles and conditions, such as a much lower pressure (100 Pa), in the PT experiment. Significant fluctuations of PT were much larger than that of SST, which may be caused by the different experimental principles and conditions, such as a much lower pressure (100 Pa), in the PT experiment.

Figure 1. Values of $\alpha/N$ and $\eta/N$ as a function of $E/N$ in C$_4$F$_7$N gas in the present work and their comparison to SF$_6$ gas.

Figure 2. Comparison of total attachment cross-sections of C$_4$F$_7$N, SF$_6$, c-C$_4$F$_8$, and CF$_3$I.

The $\alpha/N$ and $\eta/N$ measured by the SST method in this work have also been compared to the PT method measured by Chachereau et al. [14], which are plotted in Figure 3. It should be noted that the values of $\alpha/N$ and $\eta/N$ used for comparisons with the PT method were not given directly in Chachereau’s work; they were calculated from parameters such as electron drift velocity ($w_e$), ionization rate coefficient ($k_i$), and attachment rate coefficient ($k_a$). It can be found that the trends of varying $\alpha/N$ and $\eta/N$ in this work showed good agreement with PT experiments. Significantly, the fluctuation of PT was much larger than that of SST, which may be caused by the different experimental principles and conditions, such as a much lower pressure (100 Pa), in the PT experiment.

3.2. Effective Ionization Coefficients

The normalized effective ionization coefficient $(\alpha - \eta)/N$ of C$_4$F$_7$N, in a range of $E/N$ from 750 to 1150 Td, at 20 °C was obtained as well. Figure 4 presents the value $(\alpha - \eta)/N$ as a function of $E/N$ in C$_4$F$_7$N, and its comparisons with SF$_6$ [3], c-C$_4$F$_8$ [4], CF$_3$I [7], C$_4$F$_7$N [13,14], and C$_4$F$_7$N/N$_2$ mixtures [18] are reported. Notably, the $E/N$ of C$_4$F$_7$N was much greater than other kinds of gases for the same $(\alpha - \eta)/N$, which suggests that the insulation ability of C$_4$F$_7$N is much stronger. Once the C$_4$F$_7$N gas mixed with buffer gas N$_2$, the insulation performances of the mixtures were much weaker than pure C$_4$F$_7$N, since N$_2$ is an electrically neutral gas whose attachment coefficients is 0. Meanwhile,
the variety of \((\alpha - \eta)/N\) with \(E/N\) showed a linear trend for all these gases nearby the normalized critical electric field \((E/N)_{\text{lim}}\) (for \(\alpha - \eta = 0\)). Moreover, compared to the data reported, our results of normalized effective ionization coefficients in \(\text{C}_4\text{F}_7\text{N}\) were in good agreement with that of Nechmi et al. [13] as well as Chachereau [14]. Meanwhile, more values in the \(E/N\) that varied from 750 to 1150 Td were obtained in the present work.

![Figure 3](image)

**Figure 3.** (a) Comparison of values of \(\alpha/N\) measured with the steady-state Townsend (SST) method in this work and the pulsed Townsend (PT) method [14]; (b) Comparison of values of \(\eta/N\) measured with SST method in this work and PT method [14].

According to the bond length values of the \(\text{C}_4\text{F}_7\text{N}\) molecule [21], the structure of the \(\text{C}_4\text{F}_7\text{N}\) molecule could be drawn as in Figure 5. A recent study [22] shows that the bonds of C-1 to C-2 and C-1 to C-3 have the smallest bond energy, which is 3.812 eV/atom. The second smallest bond energy is 4.556 eV/atom, which belongs from C-1 to F-1. The bond energy of S-F in \(\text{SF}_6\) is 3.432 eV/atom, which is smaller than the smallest bond energy in \(\text{C}_4\text{F}_7\text{N}\). It is well known that the smaller the bond energy is, the weaker the interaction between atoms will be. Since the \(\text{C}_4\text{F}_7\text{N}\) and \(\text{SF}_6\) molecules have a strong ability to attach electrons, they can easily adsorb electrons and, hence, become negatively charged molecules. Then, these charged molecules could accelerate under an electric field, applied between two plate electrodes, and collide with other molecules. Thus, the collision may lead to the breaking of weak bonds and forming new particles such as F in \(\text{SF}_6\) and CF\(_3\) in \(\text{C}_4\text{F}_7\text{N}\). For the same electric field, the bonds of \(\text{SF}_6\) are easier to be broken than bonds C-1 to C-2 (or C-3) of \(\text{C}_4\text{F}_7\text{N}\). Consequently, the new particles formed in the \(\text{SF}_6\) gas, such as F, would further take part in the discharging process. However, the \(\text{CF}_3\) formed in \(\text{C}_4\text{F}_7\text{N}\) more easily adsorbs electrons than the F formed in \(\text{SF}_6\), since there is more F in \(\text{CF}_3\), and fluorine has strong electronegativity. Then, \(\text{SF}_6\) is more likely to exhibit ionization characteristics, which could lead to the higher effective ionization coefficients of \(\text{SF}_6\) than that of \(\text{C}_4\text{F}_7\text{N}\) for the same \(E/N\).
was about 1.73% of that measured by Chachereau et al. [14], which could testify that the experiments were of high credibility at the same time. Furthermore, it could be found that the (E/N)lim of C4F7N measured in this work was about 2.41% of that measured by Nechmi et al. [13] and slightly less than 2.68 times, which could be caused by different behaviors of ion kinetics under different gas pressures [14]. However, the dielectric strength of C4F7N was about 2.68 times that of pure SF6 gas. However, the dielectric strength of C4F7N at atmospheric pressure was about 2 times that of SF6, as reported [10], slightly less than 2.68 times, which could be caused by different behaviors of ion kinetics under different gas pressures [14]. The higher the gas pressure, the greater the effect of ion kinetics.

3.3. Critical Electric Fields

In order to more clearly compare and evaluate the insulation performance quantitatively, the (E/N)lim of these four gases have been sorted out in Table 1. It is apparent that C4F7N has a superior performance of gas insulation, as it had a high (E/N)lim value (959.19 Td). The relative deviation of (E/N)lim of C4F7N measured in this work was about 2.41% of that measured by Nechmi et al. [13] and was about 1.73% of that measured by Chachereau et al. [14], which could testify that the experiments in the present study were of high credibility at the same time. Furthermore, it could be found that the value of (E/N)lim of C4F7N was about 2.68 times that of pure SF6 gas. However, the dielectric strength of C4F7N at atmospheric pressure was about 2 times that of SF6, as reported [10], slightly less than 2.68 times, which could be caused by different behaviors of ion kinetics under different gas pressures [14]. The higher the gas pressure, the greater the effect of ion kinetics.

| Gas Type | (E/N)lim/Td |
|----------|-------------|
| C4F7N    | 959.19 [present work] |
|          | 981.84 [13] |
|          | 975 [14] |
| c-C4F8   | 408.68 [4] |
| CF3I     | 440.19 [7] |
| SF6      | 355.27 [13] |
|          | 358.66 [14] |
|          | 351.80 [16] |
4. Conclusions

In the present work, both the $a/N$ and $\eta/N$ in C$_4$F$_7$N have been measured by using the SST method for $E/N$ from 750 to 1150 Td at 20 °C, and they were compared to that of pure SF$_6$ gas. Moreover, the value of $(a - \eta)/N$ was obtained for 750 Td < $E/N$ < 1150 Td. All results measured by the SST method showed good agreement with PT experiments. The critical electric field $(E/N)_{\text{lim}}$ of C$_4$F$_7$N was about 959.19 Td. The comparison indicated that the insulation performance of C$_4$F$_7$N is superior to that of SF$_6$, and C$_4$F$_7$N could be considered as a candidate insulation gas to replace SF$_6$ in the high-voltage engineering field.

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