The Prediction of the Dielectric Breakdown Properties of 6% C_4F_7N–94% CO_2 Mixtures at 300–4000 K and 0.1–3.2 MPa

Yunkun Deng, Ke Wang, and Yuyang Yao

Abstract SF_6 is a greenhouse gas, therefore, we need to find a SF_6 substitute environment gases as an insulation and arc-quenching medium is an urgent for electrical engineer. C_4F_7N is a promising environmentally friendly insulating gas, while its boil temperature is high, therefore, CO_2 was added as a buffer gas. The dielectric strength of 6% C_4F_7N–94% CO_2 mixtures were evaluated at different pressure and temperature 0.1–3.2 MPa, and 300–4000 K. Firstly, the equilibrium compositions of 6% C_4F_7N–94% CO_2 mixtures at different gas pressures and temperatures up to 4000 K were calculated by the method of minimizing the Gibbs free energy. By Boltzmann equation analysis, the electron energy distribution function was obtained by the composition data. Finally, the critical reduced electric field ($(E/N)_{cr}$) of hot 6% C_4F_7N–94% CO_2 mixtures was determined, at which the rate of ionization is equal to attachment. The results show that in the gas temperature has an influence on 6% C_4F_7N–94% CO_2 mixing. The overall trend was that it first decreased with the increase of temperature, then rised, and finally falld. Further, the effect of barometric pressure on the $(E/N)_{cr}$ was also evident after 2000 K. The calculated results provided basic data for the post-arc breakdown of 6% C_4F_7N–94% CO_2, and have guiding significance for the engineering application of 6% C_4F_7N–94% CO_2.

Keywords Environmentally friendly insulating gas · Minimizing the Gibbs free energy · Boltzmann equation

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1 Introduction

SF_6 is mainly used for transmission and distribution equipment insulation and arc extinguishing in the power industry [1]. But given that SF_6 has an atmospheric lifetime of 3200 years (CO_2: 300–1000 years), in addtion, its global warming potential (GWP) is 23,500 times greater than CO_2 [2]. Therefore, the realization of SF_6 free has become an important issue to be solved urgently for the green development of power grid. At present, the research on SF_6 alternative gases mainly focuses on traditional gases, SF_6 mixed gases and new environmental gases. Among them, new environment-friendly gases include CF_3I, C–C_4F8, C_4F_7N, $C_5F_{10}O$ and so on [3–6].

C_4F_7N has twice the insulation strength of SF_6 and its GWP is 2100 [7]. Its liquefaction temperature is about − 4.7 °C, which is high, and the buffer gas is usually injected to meet the requirements of minimum operating temperature in engineering equipment, therefore, it is considered to be the most potential SF_6 alternative gas. Zhang et al. studied the breakdown strength and partial discharge characteristics of the C_4F_7N/CO_2 mixtures at alternating current voltages, and compared it with SF_6 [8]. Li et al. performed a breakdown experiment on C_4F_7N/N_2 gas mixture and measured the decomposition products using spherical electrodes at alternating current voltage [9]. The results shown that the main products were CF_4, C_2F_6, C_3F_8, CF_3CN, C_2F_4, C_3F_6 and C_2F_5CN after thirty times of breakdowns and the CF_4, C_2F_6 and CF_3CN contents were the highest. Li et al. analyzed the saturated vapor pressure characteristics of C_4F_7N-CO_2 mixtures based on the Antoine constants and the Antoine equation [10]. Then they discussed the application conditions at limits of environment temperature. Moreover, Zhang et al. first evaluated the electron neutral collision cross section of C_4F_7N. The set was verified by systematic comparison of Boltzmann equation analysis and experimental measurements of pure C_4F_7N, C_4F_7N/N_2 and C_4F_7N/Ar mixtures [11]. Under partial discharge (PD) and spark discharge conditions, the experimental values of decomposition products of C_4F_7N/CO_2 and $C_5F_{10}O$/air mixtures were also first presented by them. Then, ab initio molecular dynamics simulations of typical decomposition products were performed. In addition, the reliability of ab initio molecular dynamics simulation method in simulating electron induced ionization was verified [12]. GE, ABB and other companies have developed C_4F_7N as insulation medium in GIL, GIS and other products, and realized engineering application in Europe [13].

The dielectric properties of 6% C_4F_7N–94% CO_2 mixtures at 0.1–3.2 MPa and 300–4000 K were studied. First, by using the minimizing the Gibbs free energy, the equilibrium compositions of 6% C_4F_7N–94% CO_2 mixtures under different thermal states and gas pressure were calculated. By solving two-term Boltzmann equations, the electron energy distribution function (EEDF) was obtained. The value of the critical reduced electric field strength $(E/N)_{cr}$ was the electric field value corresponding to the reduced effective ionization coefficient $\alpha_{eff}/N = 0$. Finally, the $(E/N)_{cr}$ of 6% C_4F_7N–94% CO_2 mixture was determine. The calculated results provided basic data for the post-arc breakdown of 6% C_4F_7N–94% CO_2, and have guiding significance for the engineering application of 6% C_4F_7N–94% CO_2.

2 The Method of Calculation

Since the increase of gas temperature will lead to great variations in the total particle number density and gas composition, the dielectric breakdown methods of cold and hot gases are very different. The insulation properties of 6% C_4F_7N–94% CO_2 mixtures are evaluated by calculating the $(E/N)_{cr}$. The value of the$(E/N)_{cr}$ is the electric field (E/N) value corresponding to the effective ionization coefficient equals to zero. This means that the number of electrons produced by the collision ionization is balanced by the number of electrons lost by the collision attachment reaction. EEDF is important for obtaining ionization and attachment coefficients [14]. In this paper, Boltzmann equation is simplified by 2-term spherical harmonic approximation.

By minimizing the Gibbs free energy [15], the equilibrium composition of 6% C_4F_7N–94% CO_2 mixture at 0.1–3.2 MPa and 300–4000 K is calculated. The change of the composition of the 6% C_4F_7N–94% CO_2 mixture as gas temperature at different gas pressures is shown in Fig. 1. Ten speices in 6% C_4F_7N–94% CO_2 mixtures are found, which concentrations are over 10^{-6}, at the temperature range of 300–4000 K. There are CO_2, CO, CF_4, N_2, O_2, O, F, CF_2, NO and F_2, and is no C_4F_7N in the calculated component, which is due to the small amount of C_4F_7N, which will be quickly decomposed or react with other products. Among them, a large amount of CO, CF_4 and N_2 will be generated. Below 2000 K, the contents of CO_2, CO and N_2 are almost unchanged, and the content of CF_4 slowly declines with the increase of temperature. And, at this point, the content of these four gases does not change with the pressure. After 1500 K, F is decomposed, and the content of F also increases rapidly with the increase of temperature. Moreover, at the same temperature, the content of F decreases with the increase of air pressure. After 3000 K, the content is almost unchanged and does not change with the change of air pressure. At about 2000 K, O_2, O, CF_2, NO and F_2 increased with the increase of temperature. The content of O_2 is almost constant after 3000 K and does not change with the change of air pressure. When the temperature reaches a certain level, the contents of CF_2 and F_2 begin to decline. The change of components with temperature is very important for the calculation of the $(E/N)_{cr}$.

Solving the Boltzmann equation requires cross sections of all components in 6% C_4F_7N–94% CO_2 mixtures. Cross sections for all components (CO_2, CO, CF_4, N_2, O_2, O, F, CF_2, NO and F_2) are taken from the Lxcat website [16].

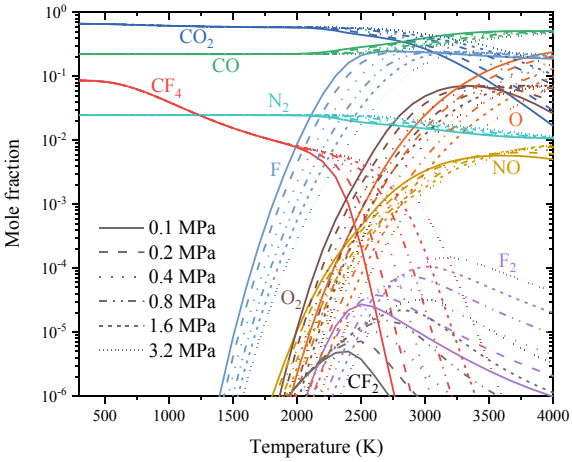

Fig. 1 Mole fractions of 6% C_4F_7N–94% CO_2 mixture with gas temperature at 0.1–3.2 MPa

3 Results and Discussion

3.1 α_{eff} and the $(E/N)_{cr}$ in 6% C_4F_7N–94% CO_2 Mixture at Room Temperature

As the electron kinetics model is adopted, the calculated $(E/N)_{cr}$ is independent of pressure, and the displayed α_{eff} is also independent of pressure. The α_{eff} of 6% C_4F_7N–94% CO_2 at room temperature is shown in Fig. 2. At lower field strengths (< 40 Td), α_{eff} is almost zero. At 40–80 Td, α_{eff} is less than 0 and decreases as E/N increases. At larger electric field, α_{eff} increases with E/N increasing. Moreover, when $E/N = 99.71$ Td, $\alpha_{eff} = 0$, which is the $(E/N)_{cr}$ of 6% C_4F_7N–94% CO_2 at room temperature.

3.2 α_{eff} and the $(E/N)_{cr}$ in 6% C_4F_7N–94% CO_2 Mixtures at High Temperature

Figure 3 shows that α_{eff} of in 6% C_4F_7N–94% CO_2 mixture at 1.6 Mpa and different gas temperatures. The overall trend of α_{eff} is almost constant at lower E/N, then decreasing and then increasing. At 1000–2000 K, the value of α_{eff} increases with the increase of temperature when the E/N is higher, so the $(E/N)_{cr}$ decreases with the increase of temperature. When the temperature is between 3000 and 4000 K, α_{eff} at 3000 K is less than that at 4000 K before 80 Td. And the $(E/N)_{cr}$ for 3000 K is less than that of 4000 K.

α_{eff} of in 6% C_4F_7N–94% CO_2 mixture at 3000 K and different gas pressures is shown in Fig. 4. As the electric field becomes larger, α_{eff} first drops and then rises.

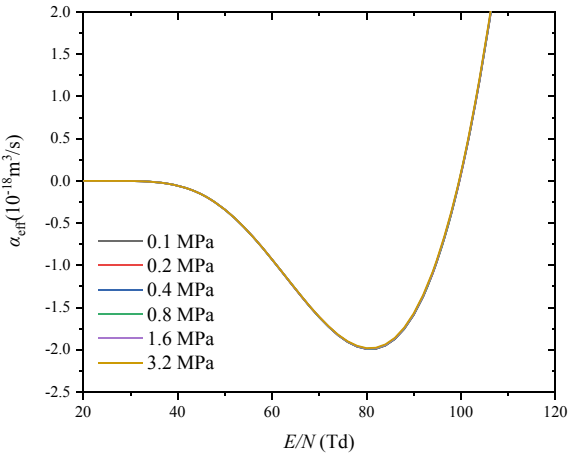

Fig. 2 α_{eff} of in 6% C_4F_7N–94% CO_2 mixture at room temperature and different gas pressures

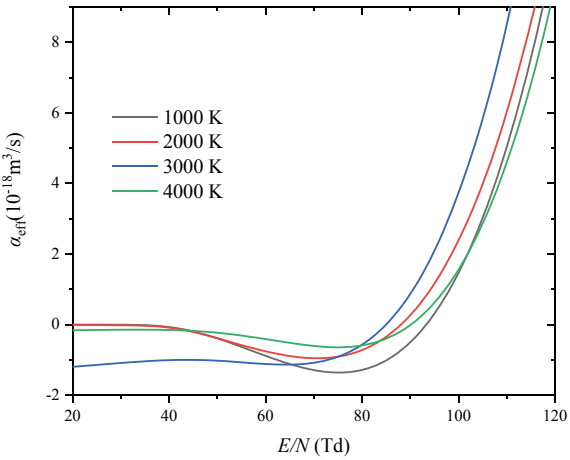

Fig. 3 The α_{eff} of in 6% C_4F_7N–94% CO_2 mixture at 1.6 MPa and different gas temperatures

α_{eff} decreases with increasing air pressure before 80 Td. After 80 Td, α_{eff} increases with increased air pressure. At 3000 K, the $(E/N)_{cr}$ varies between 80 and 90 Td, but with little regularity. This is due to the different ionization and attachment rates of the decomposition products in C_4F_7N-CO_2 mixture.

Except for 3.2 MPa, the overall trend of the $(E/N)_{cr}$ under other gas pressure is roughly the same, first decreasing, then increasing, and then decreasing with the increase of temperature. Before 2000 K, $(E/N)_{cr}$ does not change with the change of gas pressure, but decreases slowly with the increase of temperature. After 2000 K, $(E/N)_{cr}$ first decreases, then increases and then decreases with the increase of temperature. With the increase of pressure, the variation trend of $(E/N)_{cr}$ with temperature slows down, and the temperature at the inflection point of $(E/N)_{cr}$ rising and falling

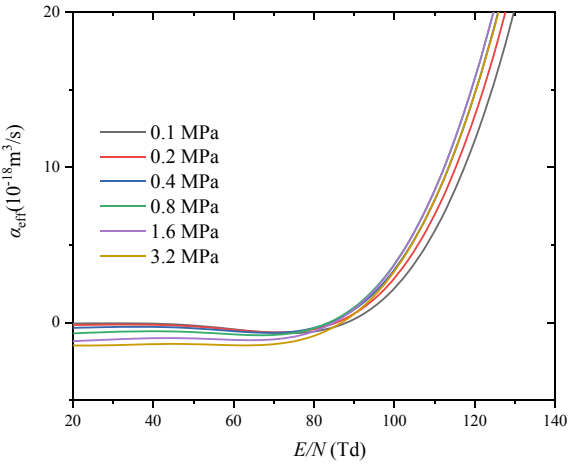

Fig. 4 Effective ionization coefficient α_{eff} of in 6% C_4F_7N–94% CO_2 mixture at different gas pressures and 3000 K

increases. When the pressure is 3.2 MPa, it is completely consistent with other pressure values and trends before 2000 K. With the further increase of temperature, it first continues to decline until the temperature reaches 3000 K, then rises, then falls and rises again. These trends are mainly caused by the formation of O_2, CF_2, F_2 and NO at 2000 K, and the rapid decline of F_2 and CF_2 at 2500–3000 K (Fig. 2).

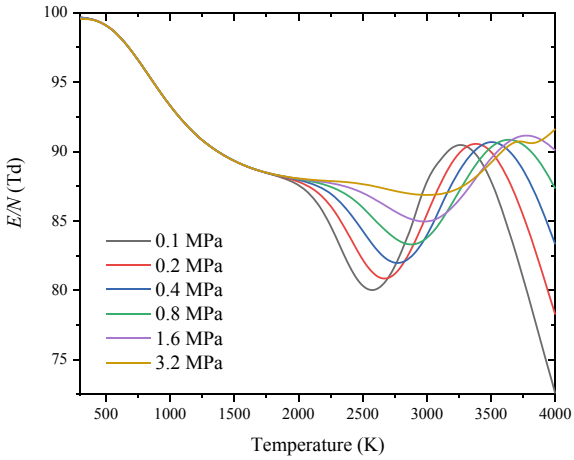

Fig. 5 $(E/N)_{cr}$ in hot 6% C_4F_7N–94% CO_2 mixtures at 0.1–3.2 MPa

4 Conclusions

The dielectric breakdown properties of 6% C_4F_7N–94% CO_2 mixtures at 0.1–3.2 MPa and 300–4000 K were studied in this paper. By using the minimizing the Gibbs free energy, the equilibrium compositions of 6% C_4F_7N–94% CO_2 mixtures under different thermal states and gas pressure were calculated. Then, by solving two-term Boltzmann equations, the EEDF was obtained. The value of the $(E/N)_{cr}$ was the electric field value corresponding to the $(\alpha\text{-}\eta)/N = 0$. Except for 3.2 MPa, the overall trend of the $(E/N)_{cr}$ under other gas pressure is roughly the same, first decreasing, then increasing, and then decreasing with the increase of temperature. Finally, the $(E/N)_{cr}$ of 6% C_4F_7N–94% CO_2 mixture was determine. The calculated results provided basic data for the post-arc breakdown of 6% C_4F_7N–94% CO_2, and have guiding significance for the engineering application of 6% C_4F_7N–94% CO_2.

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