doi:10.14311/ppt.2023.2.99
Plasma Physics and Technology **10**(2):99–102, 2023

EFFECT OF COPPER VAPOR ON RADIATION PROPERTIES OF C_4F_7N GAS MIXTURES

J. Deng, B. Zhang, X. Li*

State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, Shaanxi Province, People's Republic of China

* xwli@mail.xjtu.edu.cn

Abstract. C_4F_7N and its mixture with buffer gases are regarded as the most promising SF_6-alternative gases in gas circuit breakers. The switching arc can severely ablate the electrodes, producing copper metal vapor that combine with the C_4F_7N gas mixture to change radiation characteristics. This paper compares the net emission coefficient of C_4F_7N mixtures at various mixing ratios and assesses the effect of 20% copper vapor. It is found that adding copper vapor can greatly enhance radiation.

Keywords: SF_6-alternative gas, copper vapor, arc radiation, net emission coefficient.

1. Introduction

SF_6 is widely used in gas circuit breakers (GCB) due to its excellent insulation and arc extinguishing properties. However, SF_6 is a powerful greenhouse gas. Its Global Warming Potential (GWP) is about 25200 times than that of CO_2 [1]. Therefore, it is crucial to find an environmentally-friendly alternative gas for SF_6. In recent years, a lot of attention have been paid to the novel fluoride that C_4F_7N represents. It has a low GWP and a high dielectric strength. For gas circuit breakers, the medium cannot be liquefied at low temperatures. Due to the high boiling point of C_4F_7N, it must be combined with other buffer gases [2, 3]. According to [4], C_4F_7N/CO_2 and $C_4F_7N/CO_2/O_2$ have great potential to replace SF_6, and there have been reports on GCB products.

The research focuses on the radiative properties of C_4F_7N mixtures, which are closely related to the arc extinguishing ability. In high-temperature regions, radiation is the most important energy dissipation mechanism of the arc. Direct contact between the arc plasma and the metal material of the electrode in a circuit breaker will raise the temperature of the electrode and result in severe ablation, which will inject metal vapor into the plasma [5]. Therefore, the copper vapor needs to be taken into account while calculating the radiation properties. The fact that radiative energy transport depends on space, temperature, and frequency makes it difficult to accurately estimate. When considering computation time and accuracy, the net emission coefficient (NEC) method [6] is one of the best ways for assessing arc radiation properties. In this paper, the NECs of C_4F_7N mixtures with various C_4F_7N concentrations are calculated and the effect of Cu vapor on radiation is evaluated.

2. Theory

Radiative energy transfer is a very complex process. NEC is the net emission energy per unit volume and unit solid angle. Assumptions that are often applied in the calculation of the NEC is that:

- ☐ The plasma state is in local thermodynamic equilibrium (LTE)
- ☐ The directional distribution of the photons' propagation is isotropic
- ☐ The scattering of photons can be ignored
- ☐ The arc shape is considered as an isothermal and homogenous sphere

To obtain the NEC, the internal emission and absorption mechanisms of the arc plasma must be understood.The calculation formula is as follows:

$$\varepsilon_{\mathrm{N}}(R,T,P)=\int_0^{\infty}\varepsilon_\lambda\cdot\exp\left(-K_\lambda(T,P)\cdot R\right)\mathrm{d}\lambda \quad (1)$$

Where, ε_λ is the emission coefficient, K_λ is the absorption coefficient, R represents the radius of the arc plasma and is frequently determined empirically. The exponential term is used to describe the self-absorption of radiation emitted from the arc core.

The total radiation consists of two parts: line radiation and continuous radiation [7]. Bound electrons transit from high-lying excited states to low-lying excited states, which results in line radiation. The line emission coefficient is written as:

$$\varepsilon_{ul}^{b-b}=\frac{hc}{4\pi\lambda_{ul}}A_{ul}N_uP_\lambda \quad (2)$$

Where, ε_{ul}^{b-b} is the line emission, A_{ul} is the Einstein coefficient, N_u represents the number density of the atoms at high-lying states. P_λ is the profile of the line. Natural broadening, Doppler broadening, and pressure broadening are considered in our research, leading to a Voigt profile.

Continuous radiation is produced by free-bound and free-free transitions. For free-bound transitions:

$$\varepsilon^{f-b}=\frac{2hc^2}{\lambda^5}\left(\exp\left(-\frac{hc}{k_{\mathrm{B}}\lambda T}\right)-1\right)^{-1}N\sigma \quad (3)$$

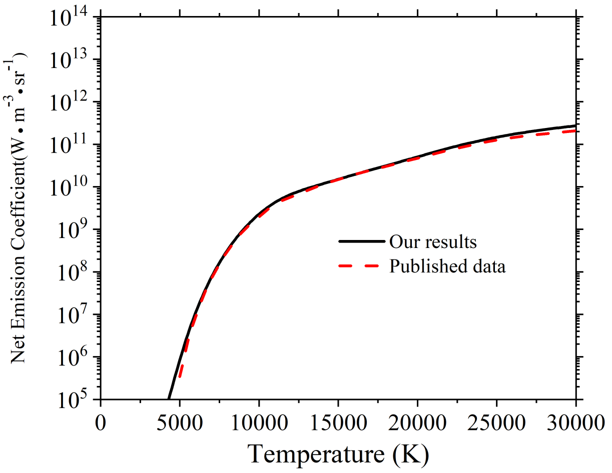

Figure 1. NEC of pure C_4F_7N at 0.1 MPa ($R = 0$ mm).

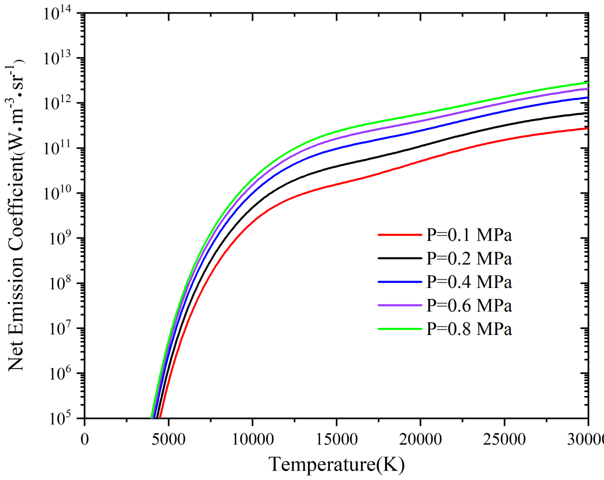

Figure 2. NECs of 3.5%C_4F_7N/86.5%CO_2/10%O_2 at different pressures ($R = 0$ mm).

Where, N is the density of the chemical species, σ is the cross section for photoionization. The free–free emission involving electrons and ions is considered. It can be calculated for thermal plasmas using a hydrogenic approximation carried out by Kramers [7]. The free–free emission for electrons and neutrals is only essential at low temperatures. The research mainly focuses on the radiation properties of the hot region of the arc and therefore does not consider this mechanism.

For spectral calculations, the atomic energy levels, Einstein coefficients, photoionization cross-sections, and free–free cross-sections are obtained from the ATBASE atomic database [8]. It includes a large number of atomic energy levels and transition data obtained by theoretical calculations for all the elements we need. In this investigation, 243600 lines for C, 311735 lines for N, 429397 lines for O, 440433 lines for F, and 42714 lines for Cu are included in the calculation. Spectrum are calculated using the PrismSPECT code [9]. On the basis of the fine spectrum (atomic lines and atomic continuum), the line-by-line method is used to calculate the NEC (almost 250 000 frequency points for one temperature). Molecular radiation is disregarded. The NEC is a useful tool in numerical modeling for characterizing radiation losses in hot regions while accounting for self-absorption.

3. Results and Discussion

3.1. Validation with published data

Figure 1 compares our results with published data [10]. Pure C_4F_7N at 0.1 MPa is selected. A good agreement can be observed in the figure, and only in the high-temperature zone our results are slightly higher. Molecular radiation is also ignored in [10]. Thus a minor difference can be attributed to the different spectral data used. It can verify the accuracy of our calculation.

3.2. Pressure effect

Figure 2 shows NECs of 3.5%C_4F_7N–86.5%CO_2–10%O_2 at different pressures, assuming an optically thin plasma. Due to an increase in radiation from a rise in density, the NEC increases as pressure increases. Additionally, because raising the pressure raises the temperatures at which ionizations and dissociations take place, it impacts the point at which the NEC curve becomes smoother.

3.3. Effects of CO_2 and O_2 on mixed gases

Figure 3 shows the NECs for different C_4F_7N gas mixtures. The gas mixture must satisfy the insulation properties and the liquefaction temperature for GCB. Generally, the percentage of C_4F_7N does not exceed 20%. 3.5% is typical for ABB products. In the study, the proportions of C_4F_7N are respectively 3.5%, 5%, 20%, and 100%, and the quantities of O_2 are 10% and 20%. It can be seen intuitively that changing O_2 and C_4F_7N gas concentrations have little effect on the NEC. This due to the fact that at high temperatures ($T > 10000$ K), the mixed gas is nearly fully decomposed and ionized into atoms and ions, and the radiation at that temperature only depends on atomic radiation. At high temperatures, the constituents of different mixed gases are very similar, and the slight variations in C and O elements have little influence on the total radiation characteristics. It can be considered that the NECs of the mixed gases at the high temperature area of the arc is only very slightly affected by the addition of CO_2 and O_2.

Of course, we can predict that there will be more pronounced disparities between various mixed gases in the low temperature zone, i.e., the region where molecular radiation cannot be ignored, which has also been confirmed in [11, 12].

3.4. Influence of copper vapor

The effect of Cu metal vapor on NEC is shown in figure 4. In comparison to 5%C_4F_7N–75%CO_2–20%O_2

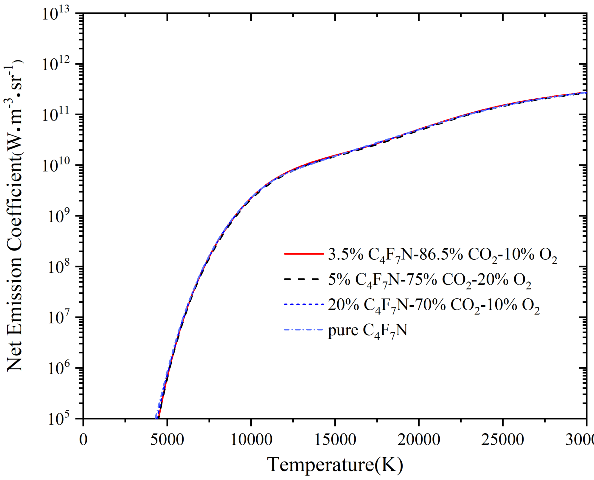

Figure 3. NECs of 3.5%C_4F_7N/86.5%CO_2/10%O_2, 5%C_4F_7N/75%CO_2/20%O_2, 20%C_4F_7N /70%CO_2 /10%O_2, and pure C_4F_7N at 0.1 MPa ($R = 0$ mm).

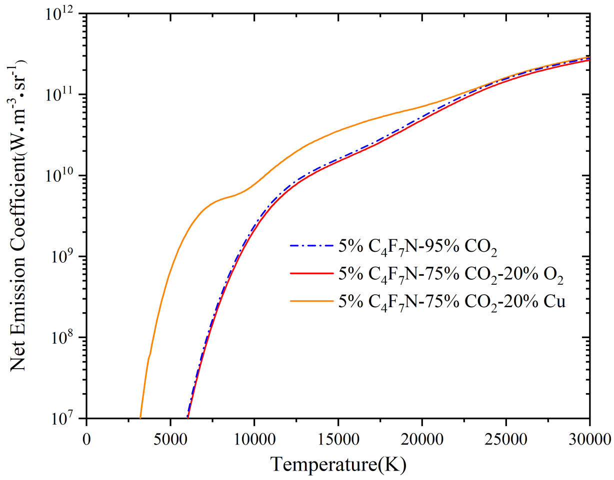

Figure 4. NECs of 5%C_4F_7N/75%CO_2/20%Cu, 5%C_4F_7N/75%CO_2/20%O_2, and 5%C_4F_7N/95%CO_2 at 0.1 MPa ($R = 0$ mm).

gas, 5%C_4F_7N–95%CO_2 gas has a slightly higher NEC. This is mostly due to the former's higher carbon content at high temperatures. As carbon has a low ionization energy and a high radiation emission, 5%C_4F_7N–95%CO_2 gas has a higher radiation emission. After adding 20%Cu vapor, the radiation of the C_4F_7N gas mixture is greatly enhanced. This is particularly apparent when the temperature is below 22000 K, as the NEC of 5%C_4F_7N–75%CO_2–20%Cu is significantly higher than that without Cu vapor. This is due to the low ionization potential of Cu metal, even lower than that of C element, resulting in an increased number density of excited energy levels of electrons and atoms at a given temperature. At high temperatures, the increase of the NEC by the added copper vapor is not so obvious.

We compare the contribution of five elements (Cu, C, O, F, N) to the total radiation in figure 5 under optically thin conditions. As analyzed above, Cu almost dominates the arc radiation in the low temperature zone. The contribution of Cu to the total radiation steadily declines as the temperature rises, whereas the contribution of other elements gradually rises. Because of their low composition, F and N always make up a very small portion of the total radiation. When the temperature is higher than 25000 K, the contribution of C and O is higher than that of Cu, and gradually occupies a dominant position. At 30000 K, the contribution of the C element can reach 60%, which is around six times that of the Cu element. As a result, the NEC of 5%C_4F_7N-75%CO_2–20%Cu is extremely near to 5%C_4F_7N–95%CO_2. It also explains that the improvement in NEC of C_4F_7N gas mixtures at high temperatures with the addition of Cu vapor is less noticeable than at low temperatures.

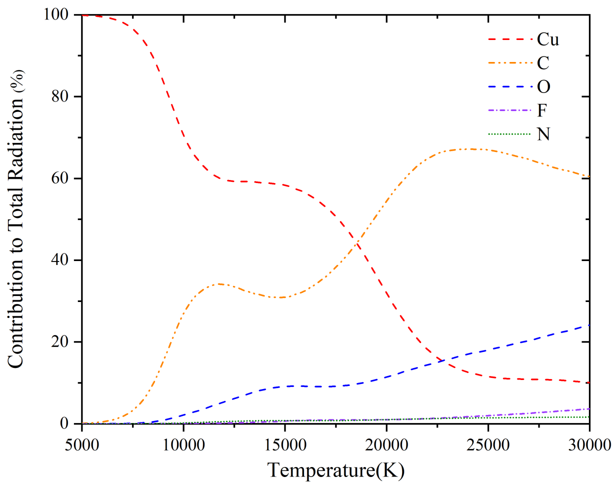

Figure 5. Contribution of the different elements to the NEC for 5%C_4F_7N/75%CO_2/20%Cu.

4. Conclusions

In this paper, the effect of adding Cu vapor on the radiative transport properties of C_4F_7N mixed gas is studied according to the NEC method. First, the NEC of 3.5%C_4F_7N–86.5%CO_2–10%O_2 at 0.1–0.8 MPa is calculated. Then the NECs under various C_4F_7N and O_2 ratios are examined, and it is discovered that there was not much of a difference among them. Finally, After adding 20% Cu vapor to the C_4F_7N gas mixtures, it is found that the NEC of the mixture significantly increases, proving that the Cu vapor produced by the contact being ablated by the arc can significantly increase the radiation ability and energy dissipation ability after entering the plasma. From this perspective, the presence of Cu vapor is beneficial to arc quenching in C_4F_7N environmentally-friendly GCBs.

Acknowledgements

The work was supported by the National Key R&D Program of China (2022YFE0129500).

References

[1] Climate Change 2021: The Physical Science Basis. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i.

[2] B. Zhang, N. Uzelac, and Y. Cao. Fluoronitrile/CO_2 mixture as an eco-friendly alternative to sf6 for medium voltage switchgears. *IEEE Trans. Dielectr. Electr. Insul.*, 25(4):1340–1350, 2018. doi:10.1109/TDEI.2018.007146.

[3] Z. Guo, X. Li, B. Li, et al. Dielectric properties of C5-PFK mixtures as a possible SF6 substitute for MV power equipment. *IEEE Trans. Dielectr. Electr. Insul.*, 26(1):129–136, 2019. doi:10.1109/TDEI.2018.007675.

[4] E. Laruelle, Y. Kieffel, and A. Ficheux. g^3–the alternative to SF_6 for high-voltage equipment. *Eco-design in Electrical Engineering*, pages 139–146, 2018. doi:10.1007/978-3-319-58172-9_15.

[5] A. Gleizes and C. Yann. Effect of metal vapours on the radiation properties of thermal plasmas. *Plasma Chem. Plasma Process.*, 37(3):581–600, 2017. doi:10.1007/s11090-016-9761-y.

[6] R. Liebermann and J. Lowke. Radiation emission coefficients for sulfur hexafluoride arc plasmas. *J. Quant. Spectrosc. Radiative Trans.*, 16(3):253–264, 1976. doi:10.1016/0022-4073(76)90067-4.

[7] M. I. Boulos, P. L. Fauchais, and E. Pfender. *Plasma Radiation Transport.* Handbook of Thermal Plasmas. Springer International Publishing, 2023.

[8] P. Wang. Ph.d. computation and application of atomic data for inertial confinement fusion plasmas, 1991.

[9] J. MacFarlane, I. Golovkin, P. Woodruff, et al. *Simulation of the ionization dynamics of aluminum irradiated by intense short-pulse lasers.* Proceeding of Inertial Fusion and Sciences Applications. 2003.

[10] Y. Wu, C. Wang, H. Sun, et al. Properties of C_4F_7N–CO_2 thermal plasmas: thermodynamic properties, transport coefficients and emission coefficients. *J. Phys. D: Appl. Phys.*, 51(15):155206, 2018. doi:10.1088/1361-6463/aab421.

[11] L. Zhong, J. Wang, J. Xu, et al. Effects of buffer gases on plasma properties and arc decaying characteristics of C_4F_7N–N_2 and C_4F_7N–CO_2 arc plasmas. *Plasma Chem. Plasma Process.*, 39(6):1379–1396, 2019. doi:10.1007/s11090-019-10015-8.

[12] V. R. Narayanan, M. Gnybida, and C. Rümpler. Transport and radiation properties of C_4F_7N–CO_2 gas mixtures with added oxygen. *J. Phys. D: Appl. Phys.*, 55(29):295502, 2022. doi:10.1088/1361-6463/ac6af5.