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STUDY OF THE INSULATING AND ARC-QUENCHING PERFORMANCE OF CO_2 AND ITS MIXTURES: A BRIEF REVIEW

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Abstract. SF_6, which is widely used as an insulating or arc-quenching medium in electrical apparatus, has a strong global warming potential. Recently, CO_2 and its mixtures attract great attention as a promising alternative gas. This paper presents our calculation and measurement results on the insulating and arc-quenching capabilities of CO_2 and its mixtures, including the discharge parameters, arc characteristics, post-arc breakdown properties, and arc-quenching capabilities. On the basis of our study and other published literatures, a discussion of and perspectives on current research and future research directions are presented as well.

Keywords: insulating, arc-quenching, CO_2.

1. Introduction

SF_6 has been widely used in high voltage apparatus, due to its excellent insulation and arc-quenching performances. However, this gas is a serious greenhouse gas, and was designated a regulated gas at COP3 (3rd Framework Convention on Climate Change) in 1997. As a result, seeking an environmentally friendly gas to replace SF_6 partially or wholly becomes even more urgent and important.

CO_2 have received lots of attentions as a potential candidate for SF_6. However, the dielectric strength of CO_2, 1.93 kV/mm, is significantly lower than that of SF_6, 8.9 kV/mm. Adding a gas with higher dielectric strength into CO_2 may be an effective way to improve its performance. The authors have carried out some investigations on the insulating and arc-quenching performances of CO_2 and its mixtures, and this paper presents our typical results and discussions on the application of CO_2 mixtures for high voltage apparatus.

2. Insulating performance

2.1. Critical reduced electric field strength at room temperature

The critical reduced electric field strength $(E/N)_{cr}$, where E is the electric field strength and N is the number density of particles, was calculated by Boltzmann analysis. The Boltzmann equation was solved by means of the zero-dimensional two-term spherical harmonic approximation. The collision cross section data for the gas molecules were taken from the Plasma Data Exchange Project. The secondary and ionizing electrons after an ionization collision were assumed to have equal energy. In addition, the three-body collisions and Coulomb interactions between charged particles were removed from consideration, and the influence of excited states was also disregarded.

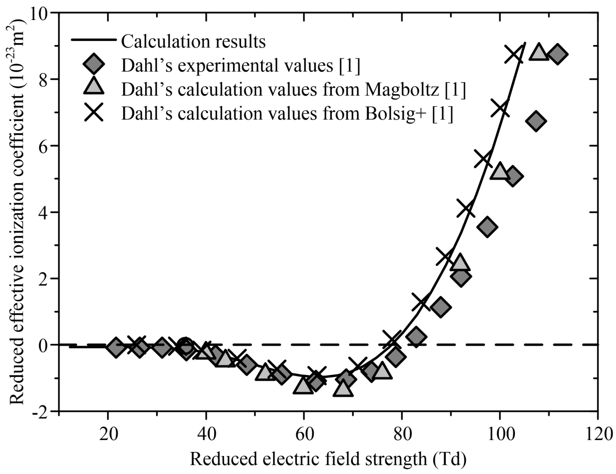

Figure 1. Comparison of $(\alpha-\eta)/N$ in CO_2 with literature data.

Fig.1 compares the calculated values of the reduced effective ionization coefficient $(\alpha-\eta)$/N of pure CO_2 gas at room temperature with the literature data [1]. A good agreement can be found between the calculated and the literature values [1].

The calculated $(E/N)_{cr}$ of the mixtures of CO_2 with 10 typical gases are plotted in Fig. 2. For comparison, the values of $(E/N)_{cr}$ of the CO_2 mixtures with C_4F_7N and $C_5F_{10}O$ were also derived from the reported experiment value in literatures [2–4].

Among these gas mixtures, the $(E/N)_{cr}$ of CO_2-C_4F_7N possesses the largest values at same mixed ratios, followed by the results of the CO_2 mixtures with $C_5F_{10}O$, CF_3I, c-C_4F_8 and SF_6. However, because of the large molecular weight, the liquefaction

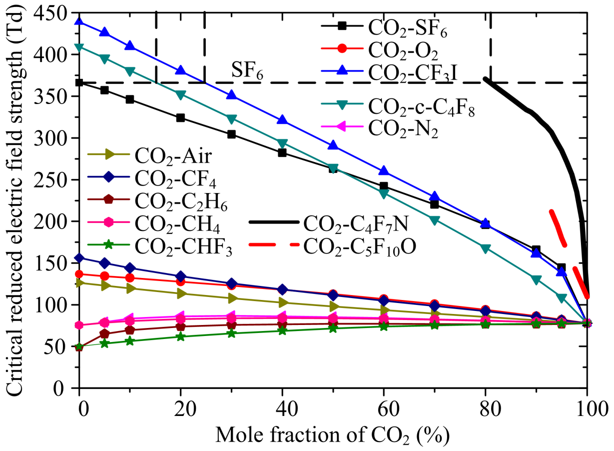

Figure 2. Comparison of $(E/N)_{cr}$ in CO_2 mixtures with different gases.

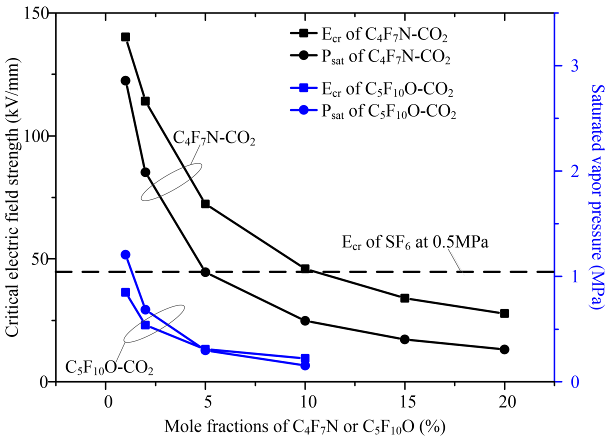

Figure 3. Saturated vapor pressure and E_{cr} characteristics of the CO_2 mixtures with C_4F_7N and $C_5F_{10}O$ at a gas temperature of −15 °C [4]

temperatures of C_4F_7N, $C_5F_{10}O$, CF_3I and c-C_4F_8 are all very high. For example, the boiling points are −4.7 °C, 26.5 °C, −22.5 °C and −8 °C of C_4F_7N, $C_5F_{10}O$, CF_3I and c-C_4F_8 at 0.1 MPa, respectively. Therefore, the analysis of the relations of saturated vapor pressure, mixed ratio and dielectric strength is necessary.

2.2. Saturated vapor pressure and dielectric strength

The saturated vapor pressures for the CO_2-C_4F_7N and CO_2-$C_5F_{10}O$ mixtures were calculated by combining the vapor-liquid equilibrium and Antoine equation in the previous paper [4] with:

$$\log P_1 = A_1 - B_1/(T + C_1) \tag{1}$$

$$\log P_2 = A_2 - B_2/(T + C_2) \tag{2}$$

$$P_1 x = P y \tag{3}$$

$$P_2(1 - x) = P(1 - y) \tag{4}$$

where P_1 and P_2 are the saturated vapor pressures of component 1 and 2, P is the saturated vapor pressure of the gas mixture, T is the liquefaction temperature of the gas mixture, A_1, B_1, C_1 and A_2, B_2, C_2 are the Antoine constants for component 1 and 2, x and y are the mole fractions for liquid phase and vapor phase of component 1 at the moment of vapor-liquid equilibrium.

Fig. 3 shows the saturated vapor pressure and E_{cr} characteristics at saturated vapor pressures of the CO_2 mixtures with C_4F_7N and $C_5F_{10}O$ [4], taking the case of −15 °C as an example. It is seen that the attainable electrical strength of CO_2-C_4F_7N is clear superior to CO_2-$C_5F_{10}O$ at saturated vapor pressures, and the maximal electrical strengths of these two mixtures are both decreased with the reduction of CO_2 concentration. Under the limitation of −15 °C, the maximum allowable operating pressure of 90 % CO_2-10 % C_4F_7N is about 0.58 MPa, and the value of E_{cr} is approximately 45.97 kV/mm, which slightly surpasses the E_{cr} of 44.76 kV/mm in pure SF_6 at 0.5 MPa. However, the dielectric strength of CO_2-$C_5F_{10}O$ is much lower than that in pure SF_6 at 0.5 MPa in the whole range. It indicates that from the view of dielectric strength, the CO_2-C_4F_7N mixture has a greater potential than the CO_2-$C_5F_{10}O$ mixture as an insulating medium.

2.3. Critical reduced electric field strength at elevated temperatures

The critical reduced electric field strengths of the CO_2 mixture with O_2 at elevated temperatures were also studied by Boltzmann analysis, in order to obtain a better understanding of the dielectric property of the hot gas and to provide the fundamental data for evaluating the dielectric recovery performance in CO_2 or its mixtures during the post-arc phase. Fig. 4 presents the $(E/N)_{cr}$ curves for different CO_2-O_2 mixtures at 0.4 MPa and elevated temperatures.

As follows from the figure, at relatively low gas temperatures, raising the mole fraction of O_2 can effectively increase the values of $(E/N)_{cr}$ in the CO_2-O_2 mixture. At gas temperatures above 3500 K, however, the $(E/N)_{cr}$ in the CO_2-O_2 mixture is reduced with the increase of the O_2 concentration. This is mainly because of the electronegativity of O_2. In addition, it is also observed that a slow increase in the $(E/N)_{cr}$ with gas temperature occurs, and this increase appears clearer in the CO_2-O_2 mixture with fewer O_2. This variation is mainly due to the dissociation of CO_2 molecules at high gas temperatures, generating CO and O_2.

The influence of gas pressure on the $(E/N)_{cr}$ in the CO_2-O_2 mixture is shown in Fig. 5. It is clear that the elevation of the gas pressure can greatly delay the variation of the $(E/N)_{cr}$ with the gas temperature to the higher temperature range.

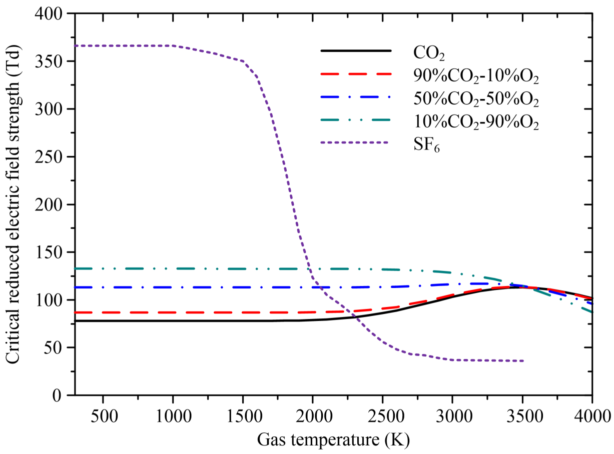

Figure 4. Critical reduced electric field strength in different CO_2-O_2 mixtures at 0.4 MPa and elevated temperatures

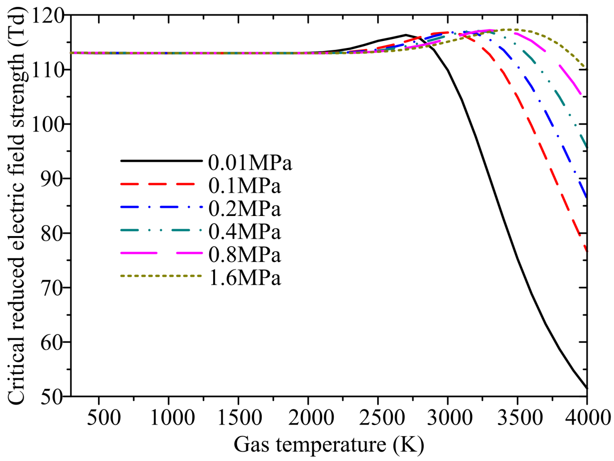

Figure 5. Critical reduced electric field strength in 50 % CO_2-50 % O_2 mixture at different gas pressures and elevated temperatures

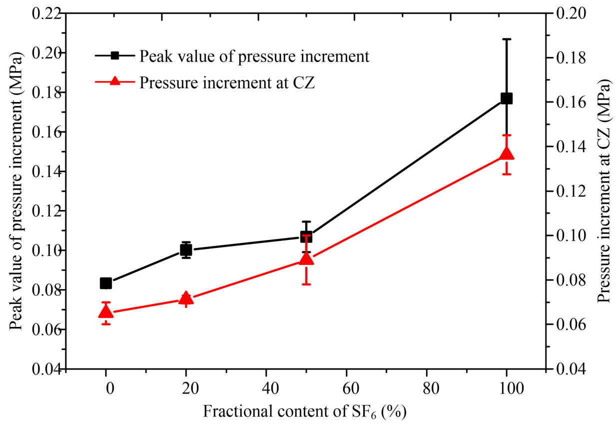

Figure 6. Peak values of the gas pressure increment and gas pressure increments at CZ in different SF_6-CO_2 mixtures at 0.6 MPa and 10 kA [5]

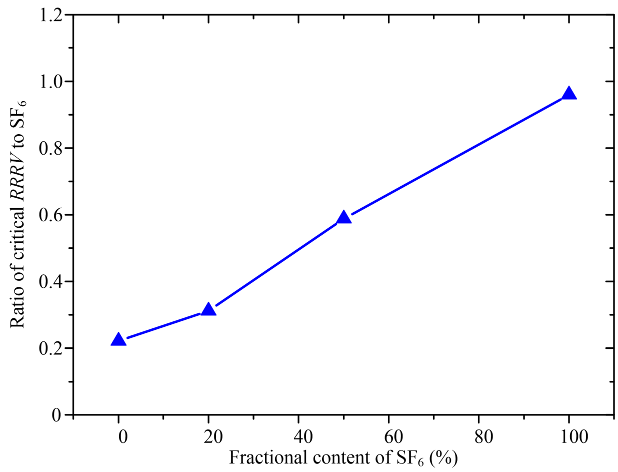

Figure 7. Ratios of critical RRRV to SF_6 in CO_2-SF_6 for different mixed ratios at 0.6 MPa and 10 kA [5]

3. Arc-quenching performance

In order to evaluating the arc-quenching performance of CO_2 and to study its arc characteristics, a series of experiments were carried out based a commercial 126 kV gas-puffer circuit breaker prototype [5].

The transient gas pressures at upstream of the throat of the nozzle were measured, and Fig. 6 gives the peak values of the gas pressure increment and the gas pressure increments at CZ in different SF_6-CO_2 mixtures at the pre-charged gas pressure of 0.6 MPa and the prospective short-circuit current of 10 kA [5]. With increasing SF_6 concentration, both ΔP_{peak} and ΔP_{CZ} increase, and non-linearly variation is also found. ΔP_{peak} and ΔP_{CZ} in CO_2 are about 47.1 % and 47.7 % of that in SF_6, respectively.

The ratios of critical values of RRRV to SF_6 in CO_2-SF_6 for different mixed ratios at the pre-charged gas pressure of 0.6 MPa and the prospective short-circuit current of 10 kA are shown in Fig. 7 [5]. The values of critical RRRV in the CO_2-SF_6 mixture for SF_6 content of 0 %, 20 % and 50 % are about 39 %, 45 % and 70 % of that of SF_6 respectively.

4. Discussions

The values of $(E/N)_{cr}$ in the CO_2 mixtures with $C_5F_{10}O$ and C_4F_7N are clear higher than that in the other mixtures without considering the liquefaction problem. By analyzing the saturated vapor pressure and E_{cr}, it is found that the dielectric strength of the CO_2-C_4F_7N mixture is much superior to the CO_2-$C_5F_{10}O$ mixture. However, the GWP value of the CO_2-$C_5F_{10}O$ mixture is much lower. More detailed and in-depth investigations are necessary. The decomposition when a discharge occurs and its influence on the insulation performance of the gas and harm to human health should be studied. It is also necessary to investigate the breakdown properties of those mixtures under different kinds of electric field, the sensitivity to metallic particles, etc.

The investigation of the interrupting capability of the CO_2-SF_6 mixture shows that large differences exist in the dielectric strength at elevated temperatures and the pressure buildup characteristics in different gases.

The matching characteristic between the gas performance and the GCB structure should be investigated. In addition, the detailed arc-quenching performances of new environment-friendly gases, including C_4F_7N and $C_5F_{10}O$, are also needed to study.

5. Conclusions

Based on the study, the following conclusions could be drawn:

1. The $(E/N)_{cr}$ of the CO_2 mixtures with C_4F_7N, $C_5F_{10}O$, CF_3I, c-C_4F_8 and SF_6 are clear higher than that of other mixtures, and that of CO_2-C_4F_7N possesses the largest values at same mixed ratios.
2. From the view of dielectric strength, the CO_2-C_4F_7N mixture has greater potential than the CO_2-$C_5F_{10}O$ mixture as an insulating medium.
3. Both the interrupting capability and the gas pressure buildup increase with the increase of the SF_6 concentration in CO_2-SF_6 mixtures, and the critical RRRV in the CO_2-SF_6 mixture for SF_6 content of 0 %, 20 % and 50 % are about 39 %, 45 % and 70 % of that of SF_6 respectively.

Acknowledgements

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