Influence of Copper Vapor on Dielectric Properties of Hot CO_2 at Different Pressures from 0.4 MPa to 0.8 MPa

Guo X. [1], Li X.[1], Zhao H. [1], Jia S. [1], Murphy A. B. [2]

[1] State key laboratory of electrical insulation and power equipment, Xi'an Jiaotong University, No. 28 XianNing West Road, Xi'an, Shaanxi Province 710049, China, email: xwli@mail.xjtu.edu.cn

[2] CSIRO Manufacturing Flagship, PO Box 218, Lindfield NSW 2070, Australia.

Abstract: The influence of copper vapor on dielectric properties of hot CO_2 at different pressures has been analyzed in this paper. By solving the Boltzmann equation, the electron energy distribution functions and the critical reduced electric field strength $(E/N)_{cr}$ were obtained. The results indicate that copper markedly reduces $(E/N)_{cr}$ of the CO_2–Cu gas mixtures because of copper's large ionization cross section. Additionally, increasing the gas pressure effectively delays the pick temperature of $(E/N)_{cr}$.

Keywords: copper vapor, CO_2, dielectric properties, Boltzmann equation

1 INTRODUCTION

SF_6 has been used as the insulating and arc-quenching medium in high-voltage gas circuit breakers for many years. At present, carbon dioxide (CO_2), as a potential substitute for SF_6 has brought about worldwide attention. Research conducted towards the properties of CO_2 has been widely carried out. Tanaka [1] provided the calculation results of thermodynamic and transport properties of CO_2, CO_2-O_2 and CO_2-H_2 mixture. Zhong [2] investigated the dielectric properties of hot SF_6-CO_2 mixture. Billoux [3] calculated the radiative transfer in CO_2-Cu mixtures at atmospheric pressure.

Copper is commonly used as contact material for its excellent thermal and electrical conductivity [4]. During the post-arc period, the dielectric properties of hot gas mixed with copper vapor may differ from those of pure arc-quenching medium gas. In this paper, we focus on the influence of copper vapor on dielectric properties of hot CO_2 at different pressures from 0.4 MPa to 0.8 MPa.

2 CALCULATION METHOD

The calculation method of prediction of critical reduced electric field strength for carbon dioxide mixed with copper vapor generally includes three steps:

(1) Calculation of composition of hot CO_2 with copper by the method based on the mass action law under the assumption of local thermodynamic equilibrium. The main species we considered are CO_2, CO, O_2, O and Cu. The mole fraction of Cu is defined [5] as follows:

$$X_{Cu} = \frac{x_{Cu(l,s)} + x_{Cu}^{g}}{x_{Cu(l,s)} + \sum x_{s}^{g}}$$

in which, $x_{Cu(l,s)}$ is mole fractions of copper in the liquid and solid phases, x_{Cu}^{g} is mole fraction of copper in the gas phase, $\sum x_{s}^{g}$ is the summation of mole fractions of all species in the gas phase. x_{Cu}^{g}, which affects the dielectric strength of gas mixtures, will change with the increasing temperature and the dissociation of CO_2. When we calculate the $(E/N)_{cr}$ of CO_2-Cu mixture, Cu in liquid and solid phases does not take into account [5].

(2) Computation of the electron energy distribution functions by Boltzmann analysis. The method of solving the Boltzmann equation was introduced in the authors' previous work [6, 7].

(3) Prediction of critical electric field strength $(E/N)_{cr}$. Equilibrium happens when the electrons produced from ionization equal to those lost due to attachment actions. Critical electric field strength $(E/N)_{cr}$ can be obtained at the balance point.

3 COMPOSITION OF HOT CO_2 WITH COPPER

Fig. 1 shows the calculation results of composition of 99% CO_2 - 1% Cu gas mixture at 0.4 MPa and 0.6 MPa. This figure indicates that CO_2 begins to markedly dissociate into CO, O_2 and O around 2000K. A comparison of the equilibrium composition between two different pressure cases reveals that increasing the gas pressure delays the dissociation of CO_2.

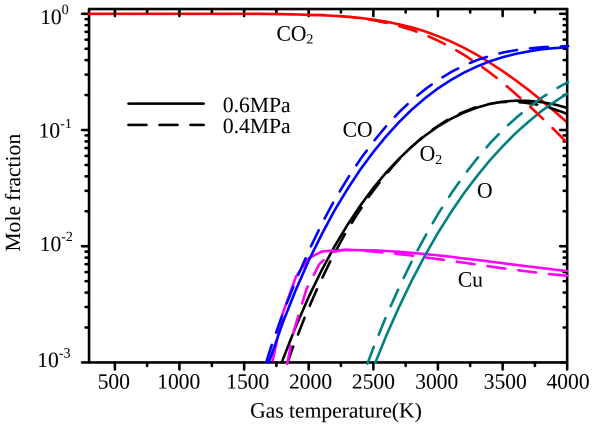

Fig.1: Composition of hot 99%CO_2 with 1% Cu atoms as a function of gas temperature at 0.6MPa and 0.4MPa

3.1 EEDF in hot CO_2 with copper

Fig. 2 illustrates the EEDFs of 99% CO_2 - 1% Cu at 0.6 MPa and 100 Td, which are calculated by solving the Boltzmann equation. The EEDFs below 1500K do not change markedly on account of the nearly constant composition. Above 1500K, the EEDFs vary obviously with an increase of temperature. The number of particles in low electron energy increases with the increasing temperature, while the average electron energy is reduced. This phenomenon can mainly be attributed to the generation of CO, which has larger vibrational excitation cross sections, and thus decays the electron kinetic energy.

4 REDUCED IONIZATION AND ATTACHMENT COEFFICIENTS IN HOT CO_2 WITH COPPER

The influence of gas temperature and gas pressure on the reduced ionization coefficients α/N and reduced attachment coefficients η/N in hot CO_2 with copper is discussed in this section.

4.1 Influence of gas temperature on α/N, η/N and (α-η)/N in a hot 99% CO_2 – 1% Cu mixture at 0.6 MPa

As shown in Fig. 3, when the gas temperature is lower than 1500K, it's difficult to distinguish the curves of the reduced ionization coefficients α/N of 99% CO_2- 1% Cu gas mixture. Above 1500 K, the copper vapor begins to affect α/N significantly with the increasing temperature. From 1500 K to 2000 K, the copper in the solid phase turned into gas phase gradually. The reduced ionization coefficient for 2000 K was enhanced substantially. As the gas temperature increased further up to 3500 K, there is a clear reduction of α/N. This phenomenon results from the generation of CO and O_2.

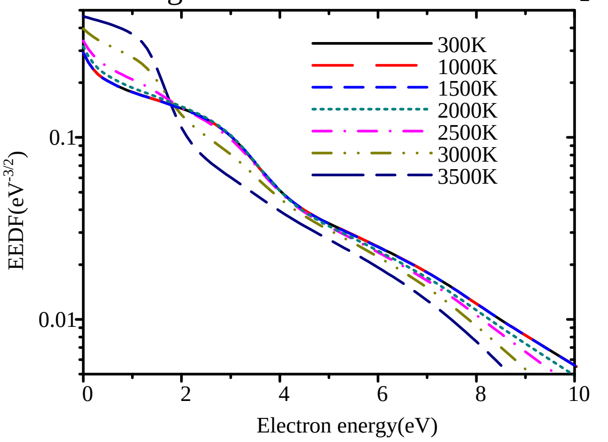

Fig.2: Electron energy distribution function (EEDF) in hot CO_2 with 1% Cu atoms for different gas temperatures at 0.6 MPa and 100 Td

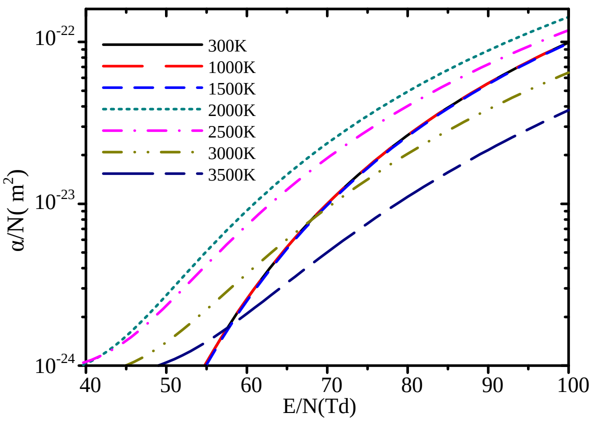

Fig.3: Reduced ionization coefficient α/N in hot CO_2 with 1% Cu atoms as a function of E/N for different gas temperatures at 0.6MPa

Reduced attachment coefficient η/N in hot CO_2 with 1% Cu atom as a function of E/N for different gas temperatures at 0.6 MPa is presented in Fig. 4. From 2000 K to 3500 K, an increasing of temperature leads to a slight reduction of η/N at E/N lower than 75 Td. This phenomenon can mainly be attributed to thermal dissociation of CO_2, which has larger attachment cross sections than CO.

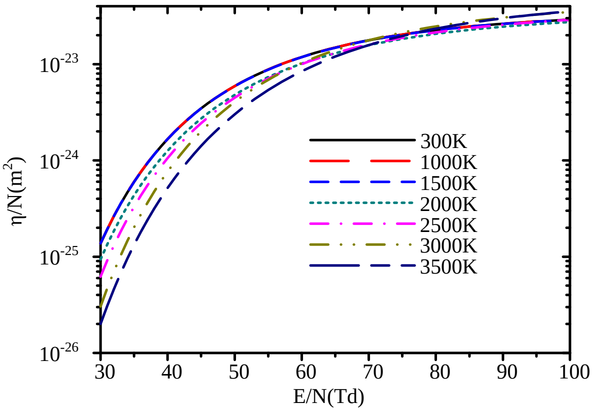

Fig.4: Reduced attachment coefficient η/N in hot CO_2 with 1% Cu atoms as a function of E/N for different gas temperatures at 0.6MPa

Based on Fig. 3 and Fig. 4, the reduced effective ionization coefficient (α–η)/N is easy to be obtained, as shown in Fig. 5. For a temperature range of 2000K~3500K, the value of (α–η)/N is strongly decreased with increasing temperature because of the strong decrease in α/N and slight reduction in η/N. When the gas temperature is below 1500K, the mole fraction of copper is lower than that of 2000K and 2500K, and thus the (α–η)/N for 1500K is lower than those for 2000K and 2500K.

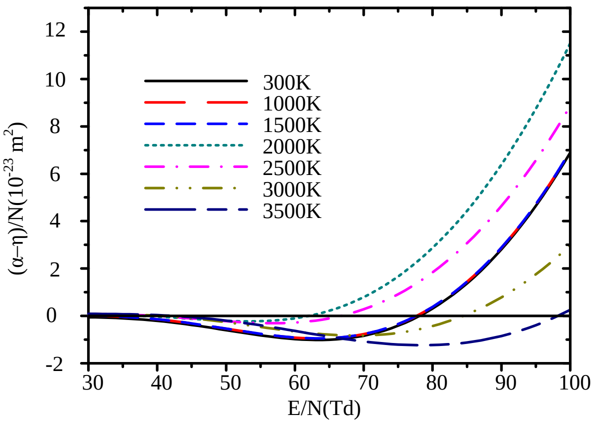

Fig.5: Reduced effective ionization coefficient (α–η)/N in hot CO_2 with 1% Cu atoms as a function of E/N for different gas temperatures at 0.6 MPa

4.2 Influence of gas pressure on α/N, η/N and (α-η)/N in a hot 99% CO_2 – 1% Cu mixture

The influence of gas pressure on reduced ionization and attachment coefficients is displayed in Fig. 6. The α/N and η/N are elevated slightly as the gas pressure increasing. This can be explained by that an increasing gas pressure delays the dissociation of CO_2. On the one hand, CO_2 has larger ionization cross section than CO and O_2, which means the probability of happening ionization collision actions with CO_2 for electrons is higher than with CO and O_2. On the other hand, as shown in Fig. 1, the mole fraction of O_2 at 0.6 MPa is higher than that at 0.4 MPa, which could slightly enhance the attachment actions.

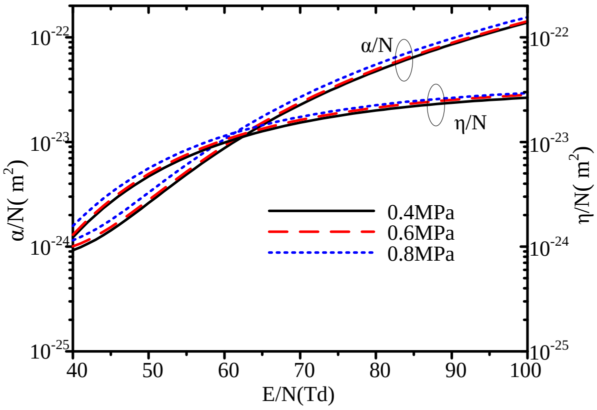

Fig.6: Reduced ionization coefficient α/N and attachment coefficient η/N in hot CO_2 at different pressures from 0.4MPa to 0.8MPa as a function of E/N at 2000 K

Fig.7 gives the reduced effective ionization coefficient in hot CO_2 with 1% Cu at different pressures and at 2000K. A growing gas pressure leads to a slight increase in (α–η)/N of the gas mixtures. The value of $(E/N)_{cr}$ decreases by 2 %, from 63.3 Td to 62 Td, as gas pressure increases from 0.4 MPa to 0.8 MPa. Therefore, it is clear that a rise of gas pressure will increase the probability of dielectric breakdown occurring in the gas mixture to a certain extent.

5 CRITICAL REDUCED ELECTRIC FIELD STRENGTH $(E/N)_{cr}$ IN HOT CO_2 WITH COPPER

Fig. 8 indicates the critical reduced electric field strength $(E/N)_{cr}$ in hot CO_2 declines markedly by adding 1% Cu at different pressures. This is attributed to copper's low ionization potential and large ionization cross section. For gas temperatures below 1500 K, almost no influence of gas temperature on the $(E/N)_{cr}$ is observed. Above 1500K, the drastic decrease in $(E/N)_{cr}$ results from the evaporation of Cu. Then, $(E/N)_{cr}$ values go up with increasing temperature as a consequence of the generation of O_2. Above 3500K, the $(E/N)_{cr}$ decrease again because of the dissociation of O_2. The minimum of $(E/N)_{cr}$ in hot CO_2 with 1% Cu at 0.4MPa is 78.4% of that in CO_2 at room temperature at 0.4MPa.

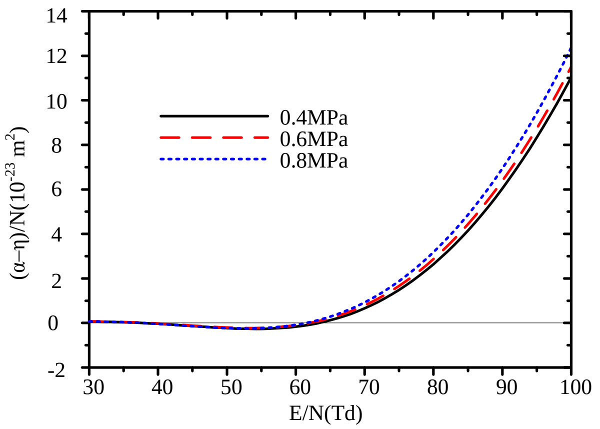

Fig.7: Reduced effective ionization coefficient (α–η)/N in hot CO_2 at different pressures from 0.4MPa to 0.8MPa as a function of E/N at 2000 K

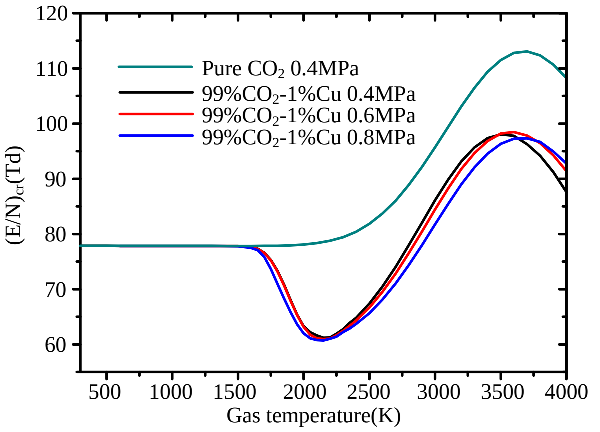

Fig.8: Critical reduced electric field strength $(E/N)_{cr}$ in hot CO_2 with 1% Cu contents at different gas pressures and in pure CO_2 at 0.4 MPa as a function of gas temperature

Besides, a growing gas pressure delays the pick temperature of critical breakdown electric fields because of the delay of the dissociation of CO_2. At 0.4MPa, the pick temperature of $(E/N)_{cr}$ comes at about 3500 K, while it comes at 3700 K at 0.8 MPa.

6 CONCLUSION

The critical reduced electric field strength $(E/N)_{cr}$ is fundamental data for the evaluation and prediction of the electric breakdown characteristics of gases during the post-arc period in high-voltage switch equipment[8].

The influence of copper vapor on dielectric properties of hot CO_2 at different pressures has been analyzed. It can be concluded that copper enhances the ionization reactions significantly on account of its large ionization cross section. Therefore, the addition of Cu could accelerate the occurrence of post-arc electric breakdown phenomenon. Additionally, increasing the gas pressure effectively delays the dissociation of CO_2 and then delays the pick temperature of critical breakdown electric fields to a certain extent.

Acknowledgements

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