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Insulation characteristics of triple mixtures of c-C₄F₈/N₂/CO₂ under lightning impulse voltage

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Abstract
This paper has researched the insulation characteristics of 10% c-C₄F₈/N₂/CO₂ mixtures under lightning impulse voltage by experiment. It is shown that the positive and negative lightning impulse breakdown voltages of 10% c-C₄F₈/N₂/CO₂ gas mixtures rise linearly as the electrode gap distance and gas pressure increase and under the same conditions, the positive lightning impulse breakdown voltage of the gas mixtures is always higher than the negative lightning impulse breakdown voltage. As the gas mixtures have a little higher liquefied temperature than SF₆ and the comprehensive GWP is about 5% of SF₆, and the positive and negative lightning impulse breakdown voltages can both reach 60% of SF₆, 10% c-C₄F₈/N₂/CO₂ gas mixtures can be applied as insulation gas in electrical equipment such as C-GIS, GIT, GIL and so on.

Keywords: SF₆ alternative, insulation characteristics, lightning impulse voltage, c-C₄F₈ gas mixtures

(Some figures may appear in colour only in the online journal)

1. Introduction

Because of high permittivity and ability of arc extinction [1, 2], SF₆ has been widely applied in different electrical equipments. However, SF₆ has greenhouse effect with Global Warming Potential (GWP) 23 900 times more than that of CO₂ [3], and it can stay for 3200 years in nature, so it has been one of the 6 regulated gases. Therefore, at the COP3 (Third Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change) which was designed in 1997, the use of SF₆ should be limited before 2020 [1, 4]. However, c-C₄F₈ has stable chemical property and is non-toxic, and its greenhouse effect is only 1/3 of SF₆, with strong electronegative property and good insulation characteristics, c-C₄F₈ is a kind of ideal alternative to replace SF₆ [1, 5–7]. As the high liquefied temperature of c-C₄F₈, it is necessary to add buffering gases such as N₂, CO₂ and so on to lower the liquefied temperature [7]. In order to make the liquefied temperature of c-C₄F₈ mixtures at the similar level of SF₆, the content of c-C₄F₈ should be lower than 15% [8], so this paper takes the 10%c-C₄F₈ mixtures for researching.

There has been many studies about the electrical characteristics of c-C₄F₈ mixtures. Zhang Liuchun researched the insulation characteristics of c-C₄F₈ mixtures by SST experiment [9]; Liu Xueli [10] and Deng et al [11] analyzed the breakdown field strength of c-C₄F₈/N₂ mixtures and c-C₄F₈/CO₂ mixtures by Monte Carlo method [10] and Boltzmann equation [11]; LI Xingwen et al analyzed the insulation characteristics of c-C₄F₈ mixtures with various gases by Boltzmann equation [12]; Belevtsev et al investigated the self-sustained volume discharge of c-C₄F₈ [13]; HIROAKI Y et al researched the discharge characteristics of c-C₄F₈ mixtures [14]; Deng Xian-qi et al
researched the insulation characteristics of c-C4F8 mixtures under the slightly non-uniform electric field [15]; Zhang Ran et al found that the insulation characteristics of c-C4F8 mixtures are equivalent to SF6 in some conditions through the AC experiment [16]; Wu Biantao researched the AC insulation characteristics of c-C4F8 mixtures under non-uniform electric field [17]; Gao Xiao-fei et al researched the interruption capability of c-C4F8 mixtures [18]. All the researches show that c-C4F8 mixtures have good insulation characteristics and thus c-C4F8 mixtures can replace SF6 in some conditions. But these researches almost pay attention to the double mixtures of c-C4F8, and as for the triple mixtures of c-C4F8, it only comes to the AC insulation characteristics of c-C4F8/N2/CO2 mixtures under non-uniform electric field [10]. Therefore, these researched cannot reflect all the insulation characteristics of c-C4F8 triple mixtures. In this case, this paper has researched the insulation characteristics of c-C4F8/N2/CO2 triple mixtures with 10% c-C4F8 under lightning impulse voltage to complement the researches of the insulation characteristics of c-C4F8 mixtures.

2. Principle of experiment

2.1. Experimental device

There is an airtight device in the experimental site. We can change the gas pressure without opening the device which can endure the gas pressure up to 1.0 MPa. What is more, the electrode can be changed between 0 mm and 100 mm without opening the device. Inside the device, there is a sphere-plate electrode with the sphere whose radius is 20 mm and the roundish plate whose diameter is 130 mm. Both the electrodes are made from cupper. When the distance between the electrodes is 5–20 mm, the electric field between the electrodes is slightly non-uniform electric field. As the majority of the electric fields in the electrical equipment are slightly non-uniform electric field, we should experiment in slightly non-uniform electric field. The schematic diagram of the experimental device is shown in figure 1.

The tank is made of aluminum alloy and a tub-insulator is installed above the tank to seal airtight. The gas pressure inside the device is measured by a digital barometer attached to the surface of the tank. We used a molecular pump to vacuumize.

2.2. Experimental method and experimental circuit

At experiment, we vacuumized the device at first. And then, we aerate the device by gas mixtures. And after sealing airtight for 24 h and above to make the gas mix enough, we can start the experiment.

The circuit diagram of lightning impulse experiment is shown in figure 2. The value of voltage is read by the oscilloscope. It is necessary to conduct the gas discharge experiment for many times in order to measure the breakdown voltage with the probability of 50%, being the 50% breakdown voltage of the gas, $U_{50\%}$ [19]. When we experiment, we should determine a certain value of voltage and conduct the gas discharge experiment. During the experiment, we define the beginning voltage as $U_b$, and define 3% of $U_b$ as $\Delta U$. If it breakdowns for consecutive multiple times, we should reduce the value of voltage by $\Delta U$; if it does not breakdown for consecutive multiple times, we should increase the value of voltage by $\Delta U$. We change the value of voltage until it breakdowns for about one half of times, and then the value of voltage is the 50% breakdown voltage. Because the 50% breakdown voltage is related to the probability, the more we experiment, the more credible the value is. Every group of experiment in this paper conducts more than 40 times, so the breakdown voltage is comparatively credible and accurate.

2.3. The liquefied temperature of the gas mixtures

The liquefied temperature of the gas mixtures can be determined by the following formula [20]:

$$T = T_b / (1 - \ln (kp)/10.5) \quad (1)$$

in the formula: $T$ is the liquefied temperature of the gas mixtures, $K$; $p$ is the gas pressure, MPa; $k$ is the content of c-C4F8 in the gas mixtures; $T_b$ is the liquefied temperature of c-C4F8, K. As the liquefied temperature of N2 is $-195.8\, ^\circ C$, the liquefied temperature of CO2 is $-78\, ^\circ C$, both are far below $-8\, ^\circ C$ which is liquefied temperature of c-C4F8, so they are both considered as ideal gas [8]. Under the gas pressure of 0.1 MPa, when the content of c-C4F8 is 10%, the liquefied temperature of gas mixtures is about $-55\, ^\circ C$ which
is equivalent to the liquefied temperature of SF₆ (−63 °C) [21], so the gas mixtures can be considered to be applied. What is more, the comprehensive GWP of 10%c-C₄F₈/N₂/CO₂ mixtures is about 5% of the GWP of SF₆, so the gas mixtures are more environmentally friendly.

3. Experimental results and analysis

3.1. Characteristics of positive lightning impulse

As there are positive and negative lightning impulse voltages, we should experiment with the positive sphere electrode and negative sphere electrode respectively. The variables of the experiment include the distance between the electrodes, the gas pressure and the content of the gas mixtures.

The experimental results show that the positive lightning impulse breakdown voltage of the gas mixtures increases as the gap distance increases without the tendency of saturation. What is more, the breakdown voltage also increases linearly as the gas pressure rises. In comparison, 10%c-C₄F₈ + 10%CO₂ gas mixtures have the highest breakdown voltage and 10%c-C₄F₈ + 90%N₂ gas mixtures have the lowest breakdown voltage. That’s to say that c-C₄F₈ is more suitable to be mixed with CO₂.

Because the positive lightning impulse endurance of CO₂ is stronger than N₂, and compared with N₂, CO₂ will not promote the ionization of c-C₄F₈. Therefore, as the content of CO₂ in the gas mixtures increases, the breakdown voltage rises. On the other hand, because N₂ affect CO₂ negatively, when the content of N₂ exceeds 30%, the rise of the gas mixture’s breakdown voltage is not obvious; and when the content of N₂ is under 30%, the gas mixture’s positive lightning impulse breakdown voltage rises more obviously as the content of CO₂ increases.

3.2. Characteristics of negative lightning impulse

The negative lightning impulse breakdown voltage of the 10%c-C₄F₈/N₂/CO₂ gas mixtures rises as the gap distance increases without the tendency of saturation. Besides, the breakdown voltage rises linearly as the gas pressure increases. This characteristic is the same to the change of positive lightning impulse breakdown voltage. Figures 3 and 4 have
shown the change curves of the positive and negative lightning impulse breakdown voltage with the change of gap distances respectively. In comparison to the curves of positive lightning impulse breakdown voltage, the curves of the negative lightning impulse voltage are more concentrated. In other word, the negative lightning voltage changes little with the change of the contents of N2 and CO2. That’s because the negative lightning impulse endurance of N2 is stronger than CO2, but N2 will promote the ionization of c-C4F8. Therefore, the negative lightning impulse breakdown voltage changes little as the content of N2 increases. And in the same conditions, the negative lightning impulse breakdown voltage is always lower than the positive lightning impulse breakdown voltage, so the electric field does not have a polar effect.

Figure 5 has shown the change curves of the negative lightning impulse breakdown voltage of 10%c-C4F8, N2, CO2 gas mixtures under 0.1 MPa gas pressure with the change of the contents of N2 and CO2. That’s because the negative lightning impulse endurance of N2 is stronger than CO2, but N2 will promote the ionization of c-C4F8. Therefore, the negative lightning impulse breakdown voltage changes little as the content of N2 increases. And in the same conditions, the negative lightning impulse breakdown voltage is always lower than the positive lightning impulse breakdown voltage, so the electric field does not have a polar effect.

Figure 4. Negative lightning impulse breakdown voltage of c-C4F8, N2, CO2 gas mixtures with different gap distances.

Figure 4. Negative lightning impulse breakdown voltage of c-C4F8, N2, CO2 gas mixtures with different gap distances.

Comparing figures 3 and 4, we can find that the curves of negative impulse lightning breakdown voltage are more concentrated than the positive one. The reason of this phenomenon is that N2 and CO2 present different insulation characteristics under the positive and negative lightning impulse voltage. In general,
the insulation characteristics of gas mixtures are influenced by the attachment and ionization of the components, as the attachment can increase the breakdown voltage and the ionization can lower the breakdown voltage. On one hand, N₂ will promote the ionization of c-C₄F₈ and lower breakdown voltage of the gas mixtures. In other hand, the positive lightning impulse endurance of CO₂ is stronger than that of N₂, but the negative lightning impulse endurance of N₂ is stronger than CO₂. Therefore, as the increase of content of CO₂ which will not promote some ionization of c-C₄F₈ and has stronger positive lightning impulse endurance than N₂ but weaker negative lightning impulse endurance than N₂, the positive lightning impulse breakdown voltage increases more than the negative lightning impulse breakdown voltage. And this reason shows up as the more concentrated curves of negative breakdown voltages.

For the same reason, we can see that the positive and negative lightning impulse breakdown voltage almost increases as the content of CO₂ increases. But there is an exception in the concentration of gases, that is, the positive lightning impulse breakdown voltage of 10% c-C₄F₈/N₂/CO₂ gas mixtures decreases first and then increases as the increase of content of CO₂. That’s because N₂ can promote the ionization of c-C₄F₈ and CO₂ which has weaker negative lightning impulse endurance than N₂, and the promotion of N₂ is stronger and the negative lightning impulse endurance of CO₂ is much weaker when the pressure is low and the electrode gap distance is long. In this case, the addition of CO₂ and the reduction of N₂ show up as the decrease of the breakdown voltage of the gas mixtures. And when the content of CO₂ is more than 40%, the promotion of N₂ decreases much more, so the breakdown voltage increases as the increase of the content of CO₂. But when the pressure is higher and the electrode gap distance is shorter, the promotion of N₂ is not strong enough to show this phenomenon.

In comparison of the positive and negative lightning impulse breakdown voltage under the same conditions, we can find that the positive lightning impulse breakdown voltage is always higher than the negative lightning breakdown voltage. This shows that this electric field does not have a polar effect [21].

Comparing the lightning impulse breakdown voltage of 10% c-C₄F₈/N₂/CO₂ gas mixtures and SF₆, the positive and negative lightning impulse breakdown voltage of the gas mixtures can reach more than 60% of the breakdown voltage of SF₆.

In a word, comparing 10% c-C₄F₈ + 90% N₂ gas mixtures and 10% c-C₄F₈ + 90% CO₂ gas mixtures, 10% c-C₄F₈ + 90% CO₂ gas mixtures have higher positive and negative lightning impulse breakdown voltage, so CO₂ is more appropriate to be mixed with c-C₄F₈ of low concentration than N₂.

4. Conclusions

In the slightly non-uniform electric field, the positive and negative lightning impulse breakdown voltage of 10% c-C₄F₈/N₂/CO₂ gas mixtures rises linearly as the electrode gap distance and gas pressure increase, without the tendency of saturation. What is more, the positive lightning impulse breakdown voltage rises as the content of CO₂ in the gas mixtures increase; for the negative impulse breakdown voltage, it changes little with the change of the content of gases, that’s because the positive lightning impulse endurance of CO₂ is stronger than N₂ and the negative lightning impulse endurance of N₂ is stronger than CO₂, but N₂ can promote the ionization of c-C₄F₈ to weaken the voltage endurance of the gas mixtures. Moreover, under the same conditions, the positive lightning impulse breakdown voltage of 10% c-C₄F₈/N₂/CO₂ gas mixtures is always higher than the negative lightning impulse breakdown voltage, which shows that there is no obvious polar effect in this electric field.

10% c-C₄F₈/N₂/CO₂ gas mixtures have a little higher liquefied temperature than SF₆, and the comprehensive GWP is about 5% of SF₆. What is more, the positive and negative lightning impulse breakdown voltages can both reach 60% of SF₆, so 10% c-C₄F₈/N₂/CO₂ gas mixtures can be applied as the alternative gas of SF₆ in electrical equipment such as cutle gas insulator switchgear, gas insulator transformer, gas insulator line and so on.

Acknowledgments

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