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Experimental Study on Power Frequency Breakdown Characteristics of C_4F_7N/CO_2 Gas Mixture Under Quasi-Homogeneous Electric Field

XIAOXING ZHANG[1], QI CHEN[1], JI ZHANG[1], YI LI[1], SONG XIAO[1], RAN ZHUO[2], AND JU TANG[1]
[1]School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
[2]Electric Power Research Institute, China Southern Power Grid Co., Ltd., Guangzhou 510080, China

Corresponding authors: Yi Li (liyi_whuee@163.com) and Song Xiao (xiaosongxs@gmail.com)

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ABSTRACT As a new environmental-friendly gas insulating medium, perfluoroisobutyronitrile (C_4F_7N) has been widely concerned in recent years due to its relatively low global warming potential and excellent dielectric strength, which has the potential to replace the most greenhouse gas, sulfur hexafluoride(SF_6). However, there are a few systematic studies on the influence of gas pressure and mixing ratio on the dielectric strength of C_4F_7N/CO_2 gas mixture at present. In this paper, the power frequency breakdown characteristics of C_4F_7N/CO_2 gas mixture under different pressure and mixing ratio conditions were tested using the gas insulation performance test platform. The optimal mixing ratio and pressure range of C_4F_7N/CO_2 gas mixture for engineering application were also discussed. It is found that the breakdown voltages of C_4F_7N/CO_2 gas mixture show a saturated growth trend with gas pressure and mixing ratio. The breakdown voltage of the gas mixture with 10% C_4F_7N can reach 80% of pure SF_6 under the same condition. The insulation performance of the gas mixture with 20% C_4F_7N can reach more than 95% of pure SF_6. Relevant results indicate that the gas mixture with 4%–12% C_4F_7N has the potential to be applied to high-voltage gas-insulated equipment.

INDEX TERMS C_4F_7N/CO_2, SF_6 alternative gas, quasi-homogeneous electric field, power frequency breakdown characteristics.

I. INTRODUCTION

SF_6 has been widely used as dielectric medium in power industry due to its excellent insulation and arc extinguishing properties [1], [2]. However, SF_6 is a severe greenhouse effect gas with the GWP value of 23,500 and atmospheric life of 3,200 years [3]. Its large amount of emission will cause great harm to the global climate.

According to the IPCC WGI Fifth Assessment Report, the atmospheric SF_6 content increased rapidly. The global annual mean SF_6 in 2011 was 7.29 ppt (part per billion), increasing by 1.65 ppt than that of 2005 [4]. In 1997, the Kyoto Protocol ranked SF_6 as one of the six major greenhouse gases [5]. The Paris Agreement in 2015 also explicitly proposed to limit the emission of greenhouse gases [6], [7]. Therefore, reducing or limiting the use of SF_6 is an urgent task. In recent years, seeking for an environmental-friendly gas insulating medium to replace SF_6 has become a hot topic.

Perfluoroisobutyronitrile (C_4F_7N) is a new type of environmental-friendly insulating gas with great application potential, which has received extensive attention from scholars all over the world in the past three years. C_4F_7N has a relatively low greenhouse effect: its GWP is 2,090 and the ozone depletion potential (ODP) is zero [8]. It is nonflammable and compatible with most electrical equipment materials. The dielectric strength of pure C_4F_7N is about twice than that of SF_6 [9], [10]. Moreover, C_4F_7N/CO_2 mixture has been characterized through a variety of toxicological studies and classified as nontoxic in acute inhalation studies, so the gas mixture requires no specific label: the LC_{50} of

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the typical C_4F_7N/CO_2 gas mixture used in high voltage equipment would be equal to roughly 120,000 ppm (part per million) [11]. The disadvantage of C_4F_7N is that its liquefaction temperature is relatively high (−4.7 °C) [12]. And it is necessary to mix C_4F_7N with CO_2, N_2 and other buffer gas to meet the lower operating temperature requirement.

At present, several achievements have been made in the insulation performance of C_4F_7N gas mixture. Li *et al.* [13] and Zhao *et al.* [14] performed a detailed calculation and measurements of the basic physical properties, dielectric strengths, and arc-quenching capabilities of C_4F_7N/CO_2 mixture. Zhang *et al.* [15] conducted an experimental study on the dielectric strength and partial discharge characteristics of C_4F_7N/CO_2 mixture under low pressure conditions (0.1 MPa-0.2 MPa). Tu *et al.* [16] and Wang *et al.* [17] conducted a pilot study on the breakdown voltage, insulator flashover voltage and the partial discharge inception voltage of C_4F_7N/CO_2 gas mixture under DC electric field. Nechmi *et al.* [18], [19] explored the effective ionization coefficient and critical breakdown electric field of C_4F_7N/CO_2 gas mixture using a steady state Townsend device, and the breakdown voltage of C_4F_7N/CO_2 gas mixture considering four mixing ratios (3.7 %, 6.8 %, 11 % and 20 %) at 0.1 MPa were also tested using sphere-to-sphere electrodes; Kieffel *et al.* [2] pointed out that the dielectric strength of C_4F_7N/CO_2 gas mixture with 18%∼20% C_4F_7N can reach the same level of SF_6. Hopf *et al.* [20] tested the insulation properties of C_4F_7N/CO_2 gas mixture under DC voltages under quasi-uniform electric field. Owens [21] analyzed the dielectric properties of C_4F_7N mixed with N_2, CO_2 and dry air using the plate-plate electrode with the gap distance 2.5mm and found that the insulation strength of C_4F_7N/CO_2 gas mixture was the best under the same conditions; Preve *et al.* [22] conducted the lightning impulse test of C_4F_7N/dry air mixture.

Nowadays, there are few systematic studies on the influence of gas pressure and mixing ratio on the insulation performance of C_4F_7N/CO_2 gas mixture. Considering that the internal electric field environment of the gas insulated equipment during its normal operation is mostly a quasi-homogeneous field [23] and CO_2 has a better arc extinguishing capability relative to N_2 [11], we tested the power frequency breakdown characteristics of C_4F_7N/CO_2 gas mixture at different gas pressures and different mixing ratios (defined as the volume fractions of C_4F_7N gas in the gas mixture) using the sphere-sphere electrode to simulate a quasi-homogeneous field in this paper. Relevant results were also compared with SF_6 under the same condition. The synergistic effect between C_4F_7N and CO_2 was also analyzed, and the feasibility of using C_4F_7N/CO_2 gas mixture in medium and high voltage equipment was discussed in combination with the liquefaction temperature. Relevant results not only reveal the influence of mixing ratio and pressure on dielectric strength of C_4F_7N/CO_2 gas mixture, but also provide significant guidance for its engineering application.

II. METHOD

A. LIQUEFACTION TEMPERATURE OF C_4F_7N/CO_2

Liquefaction temperature is an important factor that limits the practical engineering application of new insulating gas. Although C_4F_7N has excellent dielectric strength, the liquefaction temperature of −4.7 °C at 0.1 MPa makes its application extremely limited and another buffer gas is needed. As to C_4F_7N/CO_2 gas mixture, the gas pressure and mixing ratio could have a direct influence on the liquefaction temperature of gas mixture. Thus, it is necessary to determine the applicable pressure and mixing ratio range of the gas mixture based on its saturated vapor pressure characteristics.

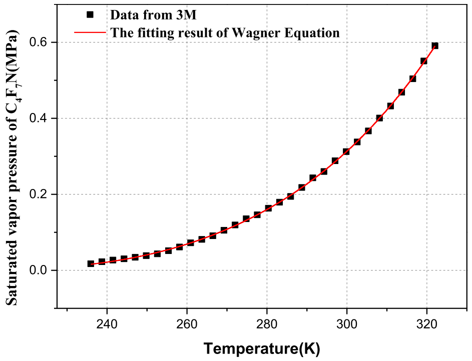


FIGURE 1. Saturated vapor pressure of C_4F_7N.

The Wagner equation is a scientific method which can be used to correlate the saturated vapor pressure and temperature data of known gases. This method has high precision for fitting experimental data. According to the C_4F_7N saturated vapor pressure data reported by 3M ^{TM} (as shown in Figure 1), the Wagner type equation of C_4F_7N can be obtained as shown in equation (1):

$$\ln p_r^* = \left(a\tau + b\tau^{1.5} + c\tau^3 + d\tau^6\right)/T_r \tag{1}$$

where $p_r^* = p/p_c$, $T_r = T/T_c$, $\tau = 1 - T_r$, p is the corresponding partial pressure (MPa) of C_4F_7N in the C_4F_7N/CO_2 gas mixture, p_c is the critical pressure (MPa), T is the thermodynamic temperature, and T_c is the critical temperature (K). T_c = 385.928K, p_c = 2.5028MPa, $a = -6.84453$, $b = -1.64783$, $c = 9.26244$, $d = -165.39152$ [24], the coefficient of determination (R^2) of the fitting equation is 0.99982.

According to Figure 1, the liquefaction temperature of pure C_4F_7N will reach 13.06 °C when the pressure increases to 0.2 MPa, which means the pure C_4F_7N has almost no engineering application value. The liquefaction temperature of C_4F_7N is greatly reduced after mixed with CO_2. Since the liquefaction temperature of CO_2 at 0.1 MPa is −78.5 °C, which is much lower than that of C_4F_7N, the gas mixture can be regarded as an ideal gas. In this case, the liquefaction temperature of the gas mixture will depend on the content of C_4F_7N.

For ideal gases, according to Dalton's law of partial pressure, the corresponding partial pressure P of C_4F_7N is the

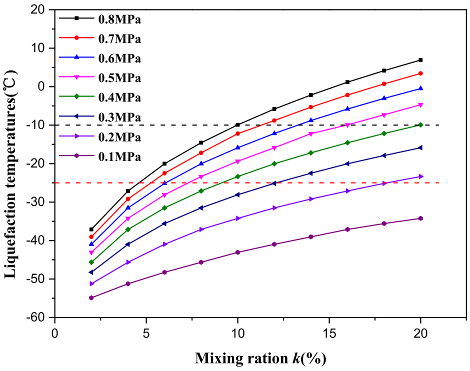


FIGURE 2. Liquefaction temperatures of C_4F_7N/CO_2 gas mixture.

TABLE 1. Experimental mixing ratio and pressure.

Group	Mixing ratio	Maximum Pressure
1	0%, 2%, 4%, 5%, 6%, 8%	0.7 MPa
2	10%, 12%, 15%	0.6 MPa
3	20%	0.4 MPa

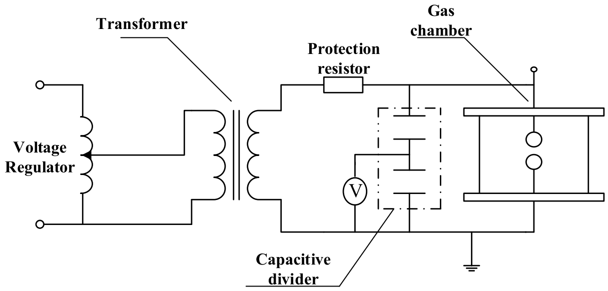


FIGURE 3. The schematic diagram of the test platform.

total pressure P_T of the C_4F_7N/CO_2 gas mixture and the volume fraction k of the C_4F_7N in the gas mixture, ie:

$$P = kP_T \tag{2}$$

Combined with Equation (1), the curve of liquefaction temperature with mixing ratio of C_4F_7N/CO_2 mixture under different pressures can be obtained, as shown in Figure 2.

It can be seen found that for the minimum operating temperature at −25 °C, the mixing ratio k should be less than 6%, 12% and 18% when the gas pressure is 0.6 MPa, 0.3 MPa and 0.2 MPa, respectively. As for the minimum operating temperature at −10 °C, the mixing ratio k should be less than 10%, 16% and 20% when the gas pressure is 0.8 MPa, 0.5 MPa and 0.4 MPa.

Considering the liquefaction temperature of the gas mixture and the working condition of the equipment, we carried out power-frequency breakdown characteristics of the gas mixture under the following conditions. (See Table 1.)

B. TEST PLATFORM

Figure 3 shows the schematic diagram of the power frequency breakdown characteristics test platform. The 50 Hz AC voltage regulator has a voltage regulation range of 0∼400V and the transformer transformation ratio is 1/250, so the secondary side maximum output voltage is 100kV. The protection resistor (10kΩ) is adopted to limit the current at the breakdown of the electrode gap and protect the experimental device. The capacitive divider has a voltage divider ratio of 1/1000 (500 pF/0.5 μF), which is used to measure the voltage applied to the test chamber. The tests are carried out using the gas chamber as shown in Figure 4.

FIGURE 4. The schematic diagram of the gas chamber.

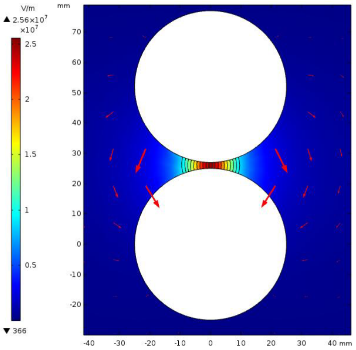


FIGURE 5. The simulation result of the ball electrodes.

The radius of the brass sphere electrode is 25mm, and the gap distance between electrodes is set to 2mm during the experiment. The electric field distribution of the electrodes is simulated by COMSOL Multiphysics (as shown in Figure 5). The electric field utilization coefficient is 1.024, which belongs to the quasi-homogeneous field [25].

C. TEST METHOD

The interior wall of the chamber and the electrodes were carefully cleaned before the test. Then the gas chamber was evacuated using a vacuum pump.

The main gas was charged first, followed by the buffer gas. Considering that C_4F_7N and CO_2 gas can be treated as an ideal gas in engineering applications, thus the mixing ratio is equal to the partial pressure ratio of the gases according to Dalton's law of partial pressure [26]. For example, the corresponding partial pressure of C_4F_7N and CO_2 is 40 kPa and 360kPa for the $10\%C_4F_7N/90\%CO_2$ gas mixture at 0.4 MPa. To ensure that C_4F_7N was thoroughly mixed with CO_2, it was allowed to stand for 12h after the end of the inflation.

During the experiment, when the gas gap broke down, the overcurrent protection regulator would automatically trip, and the voltage was recorded as the breakdown voltage of the gas mixture. Each group of test was repeated 5 times and the experimental interval was set to 5 min to ensure the insulation properties of the gas mixture cab be effectively restored after breakdown.

The C_4F_7N gas ($3M^{TM}NOVEC^{TM}4710$) is supplied by $3M^{TM}$China with a purity of 99.2%. The CO_2 and SF_6 are supplied by Wuhan Newred Special Gas Co., Ltd. with a purity of 99.999%.

D. STRATIFICATION OF C_4F_7N/CO_2 GAS MIXTURE

Due to the different density of C_4F_7N and CO_2 gas, whether stratification will occur after long-term placement is an urgent problem for researchers to figure out. Considering that the stratification is actually a slight difference in the mixing ratio of the gas mixture at different heights inside the gas chamber, the relationship between the height difference and the mixing ratio is discussed as follows.

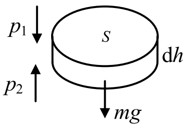


FIGURE 6. The schematic of a gas layer.

Since the gas in the closed container is under the equilibrium condition of forces [27], [28], the following relationship exists for a thin gas layer as shown in Figure 6:

$$p_1S - p_2S = mg \tag{3}$$

Because the pressure p_2 at lower height is a little larger.

$$-S\mathrm{d}p = g\rho S\mathrm{d}h \tag{4}$$

And

$$-\frac{\mathrm{d}p}{\mathrm{d}h} = g\rho = g\frac{m}{V} = g\frac{pM}{RT} \tag{5}$$

$$-\frac{\mathrm{d}p}{p} = \frac{gM}{RT}\mathrm{d}h \tag{6}$$

$$\frac{p}{p_0} = e^{-\frac{h-h_0}{H}} \tag{7}$$

Treating the gas as an ideal gas, the ratio of pressure is considered to be equal to the ratio of molecular density.

$$\frac{N}{N_0} = \frac{p}{p_0} = e^{-\frac{h-h_0}{H}} \tag{8}$$

where $H = RT/Mg$, called the scale height; M is the mass of one molecule of gas; T is the thermodynamic temperature; g is the acceleration of gravity; R is the gas constant (8.314 J/(mol•K)). Considering that the room temperature is 20 °C, the scale heights of C_4F_7N and CO_2 are 1275.117m and 5652.247m, respectively.

According to Dalton's law of partial pressure, each gas component is distributed as it exists alone, thus the relationship between the mixing ratio of the gas mixture and the height difference can be obtained according to equation (9):

$$\frac{k}{k_0} = e^{-(h-h_0)\left(\frac{1}{H_1}-\frac{1}{H_2}\right)} \tag{9}$$

where k and k_0 are the mixing ratio at the height h and the reference height h_0. The relationship between the mixing ratio and height difference can be obtained as Figure 7.

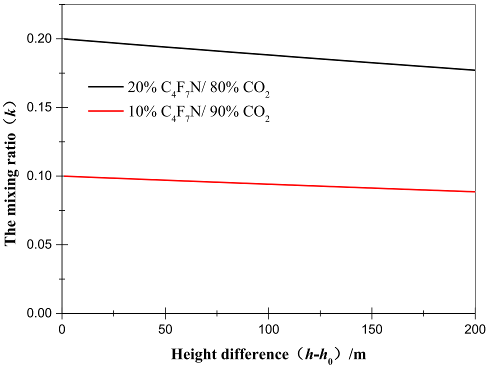


FIGURE 7. Relationship between the mixing ratio and height difference.

The height of the gas chamber used in this paper is less than 3m. For the $20\%C_4F_7N/80\%CO_2$ gas mixture, the mixing ratio at 3m is $19.964\%C_4F_7N/80.036\%CO_2$, that is, the height difference of the gas chamber has little effect on the mixing ratio.

Moreover, according to the kinetic theory of gases, the molecules are in constant, rapid and random motion, and the average speed of the gas molecules can be obtained as follows [29]:

$$\bar{v} = \sqrt{\frac{8RT}{\pi M}} \tag{10}$$

Considering that the room temperature is 25°C, the average speed of C_4F_7N and CO_2 molecules are 178.358 m/s and 375.476 m/s, respectively. If there are no chemical reaction occurs between the components, each gas is evenly distributed throughout the container, that is, the gas can be fully mixed after a enough time [30]. Therefore, the C_4F_7N/CO_2 gas mixture will not stratify during the experiment.

III. RESULTS AND DISCUSSION

A. EFFECT OF PRESSURE ON POWER FREQUENCY BREAKDOWN VOLTAGE OF C_4F_7N/CO_2 MIXTURE

Figure 8 shows the power frequency breakdown voltages of C_4F_7N/CO_2 gas mixture and SF_6 at different pressures. It can be found that the influence of pressure on the breakdown voltages of gas mixture is consistent. The breakdown voltage increases linearly with the pressure within 0.1MPa~0.5MPa. When the gas pressure reach above 0.5MPa, the breakdown voltage tends to be saturated. The occurrence of this phenomenon can be attributed to the fact that C_4F_7N is more

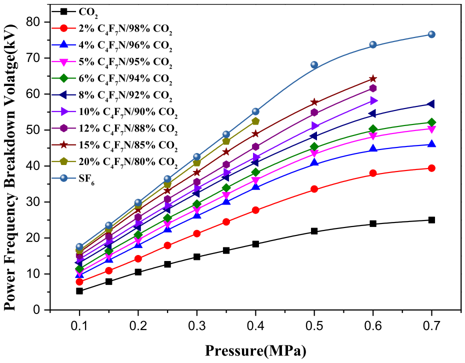


FIGURE 8. Influence of pressure on the power frequency breakdown voltages of C_4F_7N/CO_2 gas mixture at different mixing ratios.

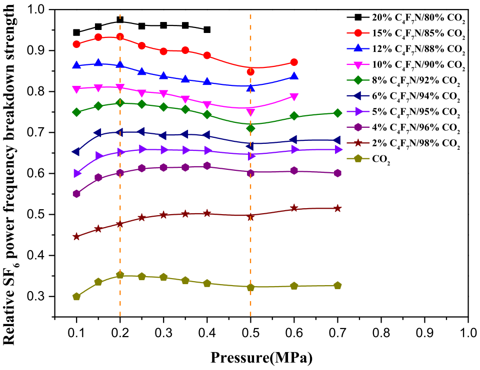


FIGURE 9. Influence of pressure on relative SF6 power frequency breakdown strength of C_4F_7N/CO_2 gas mixture at different mixing ratios.

sensitive to the unevenness of the electric field under high pressure.

In fact, with the increase of gas pressure, the mean free path length of electrons in the mixture is compressed, thus the kinetic energy accumulated by electrons between the two collisions is reduced, thereby reducing the generation of ionization. Therefore, the breakdown voltage increases with the pressure. However, the growth rate of the breakdown voltage decreases after the gas pressure reaches to a certain level, showing a saturated growth trend (see Figure 8). This may due to some factors such as the surface state of electrodes and the electrodes area. These factors has little effect on the breakdown voltage under the low pressure conditions, while their influence will be amplified when the pressure is high [31]. Considering that the influence of the surface state of electrode will be amplified under high pressure, when there is a bump on the surface, the local electric field strength at the point of the bump is much stronger than the average electric field in the gas gap. At this time, an extremely intense ionization process will be generated near the bump, and a large amount of electron collapse will be rapidly generated with electron collapse expanding toward the other end electrode. When the applied voltage is not high enough for the discharge to expand through the entire gas gap, a stable corona discharge is formed. During corona discharge, the ionization and luminescence of the gas are limited to a thin layer called ''corona layer'' near the surface of the electrode. In the layer, the electric field outside the corona layer is weak, and the gas does not collide and ionize, thus the breakdown voltage increases. The partial discharge inception voltage (PDIV) under low gas pressure conditions increases with the gas pressure, and the shielding effect of the corona layer makes the breakdown voltage significantly higher than the PDIV. When the gas pressure reaches a certain level, the migration and diffusion of the space charge are limited, and the corona layer is compressed and the shielding effect is weakened, thus the growth rate of breakdown voltage is significantly reduced.

In order to compare the insulation performance of C_4F_7N/CO_2 gas mixture with pure SF_6 gas more clearly, the ratio of breakdown voltage of the two gases under the same conditions is defined as the relative SF_6 power frequency breakdown strength. The relationship between the relative SF_6 power frequency breakdown strength and the pressure of C_4F_7N/CO_2 gas mixture at different mixing ratios is shown in Figure 9.

It can be found that the relative power-frequency breakdown strength of the gas mixture increases first and then decreases slightly with the increase of the pressure, and has a minimum value at 0.5 MPa, and finally rises. This trend indicates that at low pressure (<0.2 MPa), the growth rate of the breakdown voltage of the C_4F_7N/CO_2 gas mixture is better than that of SF_6, that is, the increase of pressure under low pressure conditions has a greater influence on the gas mixture than that on SF_6. When the pressure increases to 0.2~0.5MPa, the growth rate of the breakdown voltage of pure SF_6 will be slightly higher than that of C_4F_7N/CO_2 gas mixture. The growth rate will decline when the pressure rises to 0.5 MPa, which corresponds to the inflection point of the trend in Figure 8. As to the pressure higher than 0.5MPa, the relative power frequency breakdown strength of the gas mixture will rise slowly, indicating that the saturation trend of the gas mixture is weaker than that of SF_6.

B. EFFECT OF MIXING RATIO ON POWER FREQUENCY BREAKDOWN VOLTAGE OF C_4F_7N/CO_2 MIXTURE

Figure 10 shows the relationship between the breakdown voltage of C_4F_7N/CO_2 gas mixture and the mixing ratio *k* at different pressures.

It can be found that the addition of a small amount of C_4F_7N can significantly increase the breakdown voltage of CO_2. This phenomenon is more obvious under high pressure conditions. For example, when the mixing ratio *k* increases from 0% to 2%, the breakdown voltage growth rate is 35.20%, 51.61% and 58.48% under 0.2MPa, 0.4MPa and 0.6MPa, respectively. As *k* continues to increase, the growth rate of the breakdown voltage becomes smaller. For example, when the mixing ratio increases by 5%, the growth rate of the breakdown voltage is about 98%, 17%, 15% and 7% under 0.4MPa, respectively, presenting a saturated growth trend.

Actually, C_4F_7N is a strong electronegative gas which can easily adsorb free electrons to form negative ions. The mean free path length of ions is shorter than that of electrons,

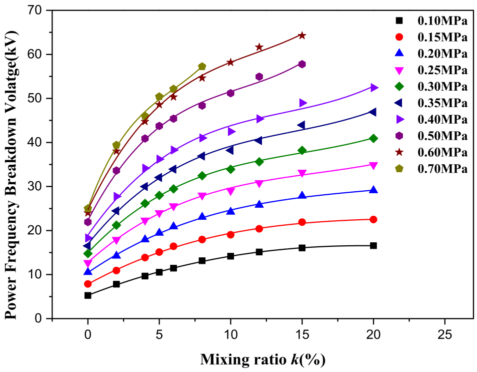


FIGURE 10. **Influence of mixing ratio on the power frequency breakdown voltages of C_4F_7N/CO_2 gas mixture at different pressures.**

so the accumulated kinetic energy of ions is less than that of electrons. The ions are more likely to lose their accumulated kinetic energy during the collision with the gas molecules, which will reduce the probability of impact ionization of gas molecules, and ultimately hinder the development of gas discharge. Moreover, considering that the free electrons have a smaller mean free path length in a gas with a larger molecular radius [25], and the radius of C_4F_7N molecule is much larger than that of CO_2 molecule. Therefore, the higher the content of C_4F_7N in the gas mixture, the smaller the mean free path length of the free electrons in the C_4F_7N/CO_2 gas mixture will be, which ultimately weakens its ability to cause impact ionization.

Besides, due to the fact that the chance of recombination between positive and negative ions is much higher than that between positive ions and electrons [31], the recombination probability increases when free electrons adsorbed by electronegative gas molecule and change into negative ions. Then the amount of charged particles will be reduced and the dielectric strength of the gas insulating medium can be enhanced. It should be noted that the free electrons generated by various factors in the gas mixture cannot increase indefinitely. When the content of C_4F_7N in the C_4F_7N/CO_2 gas mixture further increased, most of the free electrons have been captured by C_4F_7N to form negative ions, so the breakdown voltage will not significantly increase, that is, the breakdown voltage of the gas mixture will be saturated as the mixing ratio *k* increases.

Figure. 11 is the relationship between relative SF_6 power frequency breakdown strength of the gas mixture and the mixing ratio *k*.

It can be found that the relative power frequency breakdown strength of the gas mixture exhibits a saturated growth trend with the mixing ratio. The insulation performance of the gas mixture with 5%, 10% and 15% C_4F_7N can reach 60%∼65%, 80% and 90% of pure SF_6 under the same condition, respectively. The insulation performance of 20% C_4F_7N/80%CO_2 gas mixture can reach to more than 95% of SF_6, which is consistent with the conclusion in literature [32].

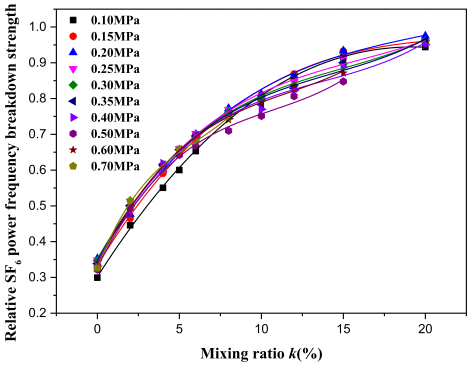


FIGURE 11. **Influence of mixing ratio on relative SF6 power frequency breakdown strength of C_4F_7N/CO_2 gas mixture at different pressures.**

TABLE 2. **Synergistic effect coefficient calculation result.**

Pressure(MPa)	Mixing ratio *k*							
	2%	4%	5%	6%	8%	10%	12%	15%
0.10	0.378	0.392	0.381	0.352	0.288	0.269	0.216	0.139
0.15	0.424	0.360	0.341	0.305	0.300	0.310	0.251	0.214
0.20	0.446	0.376	0.360	0.339	0.321	0.355	0.324	0.213
0.25	0.360	0.328	0.322	0.312	0.301	0.359	0.339	0.254
0.30	0.338	0.324	0.326	0.334	0.320	0.367	0.382	0.347
0.35	0.314	0.314	0.320	0.319	0.327	0.400	0.407	0.322
0.40	0.291	0.289	0.303	0.303	0.335	0.413	0.392	0.338
0.50	0.318	0.323	0.321	0.351	0.406	0.450	0.343	-
0.60	0.288	0.341	0.319	0.353	0.359	0.355	0.277	-
0.70	0.412	0.535	0.448	0.562	-	-	-	-

C. SYNERGISTIC EFFECT OF C_4F_7N/CO_2 MIXTURE

In order to further analyze the influence of mixing ratio *k* on the insulation performance of the C_4F_7N/CO_2 gas mixture, the synergistic effect calculation formula is used to calculate the synergistic effect in the mixing ratio in this paper. In equation (11), U_1 is defined as the breakdown voltage at the highest C_4F_7N content under a certain pressure condition in the experimental interval, U_2 is the breakdown voltage of CO_2 ($k = 0\%$) at the same pressure as U_1, and U_m is the breakdown voltage of the gas mixture at other mixing ratios under the same condition. C is the synergistic effect coefficient, K is the equivalent mixing ratio in this experimental interval, equal to $k(U_m)/\ k(U_1)$ [33].

$$U_m = U_2 + \frac{K\ (U_1 - U_2)}{K + (1 - K)C}, \quad U_1 > U_2 \tag{11}$$

The calculated C values are shown in Table 2. It can be found that the synergistic effect coefficient C of the gas mixture with 2%-15%C_4F_7N is between 0.1 and 0.6, which belongs to synergistic effect type [34]. The smaller C means a more pronounced synergistic effect [35], that is, the gas mixture at the mixing ratio having the smaller C under the same pressure condition is much more suitable using as the insulating medium.

According to Table 2, the smaller C value exists under a high mixing ratio and low pressure (0.10 MPa-0.25 MPa) conditions. But with the increase of gas pressure, the mixing ratio where smaller C values exists reduced. Thus, the arrangement of combination between gas pressure and mixing ratio is crucial.

D. FEASIBILITY ANALYSIS OF APPLICATION OF C_4F_7N/CO_2 GAS MIXTURE

Combined with the liquefaction temperature and power frequency breakdown characteristics of the C_4F_7N/CO_2 gas mixture discussed above, the mixing ratio and pressure range with practical application value can be obtained.

From the perspective of pressure, the gas pressure should not be too high. Firstly, the gas mixture under high pressure conditions will be easily liquefied. Secondly, the improvement effect of the breakdown voltage caused by the gas pressure rise is not very great under high pressure conditions. Finally, the high pressure will pose a safety hazard to the equipment. Therefore, in combination with the test results in Figure 8, the application pressure of the gas mixture is recommended to be less than 0.6 MPa.

From the perspective of liquefaction temperature, combined with the calculated results in Figure 2, when the gas pressure is not higher than 0.6 MPa, the mixing ratio of the C_4F_7N/CO_2 gas mixture is recommended to be less than 6% and 12% to meet the minimum operating temperature of −25 °C and −10 °C, respectively.

From the perspective of environmental protection, the total GWP of the gas mixture can be obtained from the sum of the weight fractions of the individual substances multiplied by their GWP [32], calculated as follows:

$$\mathrm{GWP} = \frac{k * 195 * 2090 + (1-k) * 44 * 1}{k * 195 + (1-k) * 44} \tag{12}$$

Figure 12 shows the relationship between the GWP value and the mixing ratio of the C_4F_7N/CO_2 gas mixture. It can be found that the gas mixture with C_4F_7N content of 12% have a GWP value of 800, which is only 3.4% of SF_6. Therefore, the use of the C_4F_7N/CO_2 gas mixture can effectively reduce the greenhouse effect.

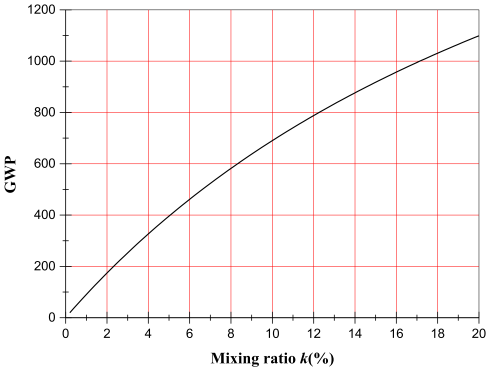


FIGURE 12. The GWP of C_4F_7N/CO_2 gas mixture.

For cabinet gas insulated switchgear (C-GIS), the working pressure is generally not higher than 0.20 MPa (absolute pressure). If C_4F_7N/CO_2 gas mixture is used as the insulating medium, the C_4F_7N content can be added to 12% or more, which can meet the minimum operating temperature of −25 °C and achieve more than 85% of SF_6 insulation performance.

Similarly, for gas insulated transmission lines (GIL) and gas insulated switchgear (GIS), the working pressure is 0.3∼0.4MPa and 0.4∼0.6MPa respectively when using pure SF_6 as the insulating medium [36]. For C_4F_7N/CO_2 gas mixture using as the insulating medium in these equipment, the C_4F_7N content in GIL and GIS should not exceed 10% and 6% to meet the minimum operating temperature of −25°C and −10°C separately.

IV. CONCLUSION

In this paper, the power frequency breakdown characteristics of C_4F_7N/CO_2 gas mixture under quasi-homogeneous field were tested using the gas insulation performance test platform. The influence of pressure and mixing ratio on the breakdown voltage of the gas mixture were systematically analyzed and compared with SF_6. The content range of C_4F_7N with practical application potential was also obtained, which provided guidance for further research and application of C_4F_7N/CO_2 gas mixture. Relevant results were obtained as follows:

(1) The power frequency breakdown voltages of C_4F_7N/CO_2 gas mixture show the saturated growth trend with the increase of gas pressure and mixing ratio. The addition of a small amount of C_4F_7N (2%) can greatly improve the breakdown voltage of CO_2 by about 50%.

(2) The gas mixture with 10% C_4F_7N content can reach 80% of the SF_6 insulation strength, and the gas mixture with 20% C_4F_7N content can reach more than 95% of SF_6 insulation strength, which is close to the insulation performance of SF_6.

(3) C_4F_7N and CO_2 gas have a synergistic effect and the arrangement of combination between gas pressure and mixing ratio is crucial.

(4) Combined with the liquefaction temperature and power frequency breakdown characteristics of the gas mixture, the gas mixture with 4%∼12%C_4F_7N has great engineering application potential, and the GWP value will be reduced by more than 96% compared with SF_6.

REFERENCES

[1] P. Glaubitz *et al.*, “CIGRE position paper on the application of SF_6 in transmission and distribution networks,” *Electra*, vol. 34, no. 274, pp. 34–39, 2014.

[2] Y. Kieffel, T. Irwin, P. Ponchon, and J. Owens, “Green gas to replace SF_6 in electrical grids,” *IEEE Power Energy Mag.*, vol. 14, no. 2, pp. 32–39, Mar./Apr. 2016.

[3] M. Seeger *et al.*, “Recent trends in development of high voltage circuit breakers with SF_6 alternative gases,” in *Proc. 22nd Symp. Phys. Switching Arc*, 2017, pp. 1–5.

[4] *The IPCC Fifth Assessment Report Climate Change 2013?: The Physical Science Basis*, IPCC Working Group I, Stockholm, Sweden, Sep. 2013.

[5] Y. Fu, M. Rong, X. Wang, and A. Yang, “Rate constants of $C_5F_{10}O$ decomposition reactions at temperatures of 300–3500 K,” *J. Phys. D, Appl. Phys.*, vol. 52, no. 3, pp. 035202–035216, 2018.

[6] J. Rogelj *et al.*, “Paris agreement climate proposals need a boost to keep warming well below 2 °C,” *Nature*, vol. 534, no. 7609, pp. 631–639, 2016.

[7] J. A. Patz and J. J. West, "The Paris agreement could saves lives in China," *Lancet Planetary Health*, vol. 2, no. 4, pp. e147–e148, 2018.

[8] X. Zhang *et al.*, "Reactive molecular dynamics study of the decomposition mechanism of the environmentally friendly insulating medium C_3F_7CN," *RSC Adv.*, vol. 7, no. 80, pp. 50663–50671, 2017.

[9] J. Xiong, X. Li, J. Wu, X. Guo, and H. Zhao, "Calculations of total electron-impact ionization cross sections for fluoroketone $C_5F_{10}O$ and fluoronitrile C_4F_7N using modified Deutsch–Märk formula," *J. Phys. D, Appl. Phys.*, vol. 50, no. 44, pp. 445206–445212, 2017.

[10] A. Romero, L. Rácz, A. Mátrai, T. Bokor, and R. Cselkó, "A review of sulfur-hexafluoride reduction by dielectric coatings and alternative gases," in *Proc. 6th Int. Youth Conf. Energy (IYCE)*, Jun. 2017, pp. 1–5.

[11] Y. Kieffel, F. Biquez, P. Ponchon, and T. Irwin, "SF_6 alternative development for high voltage switchgears," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2015, pp. 1–5.

[12] Y. Wu *et al.*, "Properties of C_4F_7N-CO_2 thermal plasmas: Thermodynamic properties, transport coefficients and emission coefficients," *J. Phys. D, Appl. Phys.*, vol. 51, no. 15, pp. 155206–155217, 2018.

[13] X. Li, H. Zhao, and A. B. Murphy, "SF_6-alternative gases for application in gas-insulated switchgear," *J. Phys. D, Appl. Phys.*, vol. 51, no. 15, pp. 153001–153019, 2018.

[14] H. Zhao, X. Li, N. Tang, X. Jiang, Z. Guo, and H. Lin, "Dielectric properties of fluoronitriles/CO_2 and SF_6/N_2 mixtures as a possible SF_6-substitute gas," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1332–1339, Aug. 2018.

[15] B. Zhang, N. Uzelac, and Y. Cao, "Fluoronitrile/CO_2 mixture as an eco-friendly alternative to SF_6 for medium voltage switchgears," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1340–1350, Aug. 2018.

[16] Y. Tu, Y. Cheng, C. Wang, X. Ai, F. Zhou, and G. Chen, "Insulation characteristics of fluoronitriles/CO_2 gas mixture under DC electric field," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1324–1331, Aug. 2018.

[17] C. Wang *et al.*, "Characteristics of C_3F_7CN/CO_2 as an alternative to SF_6 in HVDC-GIL systems," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1351–1356, Aug. 2018.

[18] H. E. Nechml, A. Beroual, A. Girodet, and P. Vinson, "Effective ionization coefficients and limiting field strength of fluoronitriles-CO_2 mixtures," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 2, pp. 886–892, Apr. 2017.

[19] H. E. Nechmi, A. Beroual, A. Girodet, and P. Vinson, "Fluoronitriles/CO_2 gas mixture as promising substitute to SF_6 for insulation in high voltage applications," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2587–2593, Oct. 2016.

[20] A. Hopf, J. A. Britton, M. Rossner, and F. Berger, "Dielectric strength of SF_6 substitutes, alternative insulation gases and PFC-gas-mixtures," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Jun. 2017, pp. 209–212.

[21] J. G. Owens, "Greenhouse gas emission reductions through use of a sustainable alternative to SF_6," in *Proc. 34th Electr. Insul. Conf. (EIC)*, Jun. 2016, pp. 535–538.

[22] C. Preve, R. Maladen, and D. Piccoz, "Method for validation of new eco-friendly insulating gases for medium voltage equipment," in *Proc. IEEE Int. Conf. Dielectr. (ICD)*, vol. 1, Jun. 2016, pp. 235–240.

[23] Y. Deng, Y. Ma, X. Chen, S. Zhang, and X. Chen, "AC breakdown characteristics of CF_3I-N_2 gas mixtures in condition of quasi-homogeneous and extremely non-uniform electric field," *High Voltage Eng.*, vol. 43, no. 3, pp. 754–764, 2017.

[24] Y. Li *et al.*, "Study on the dielectric properties of C_4F_7N/N_2 mixture under highly non-uniform electric field," *IEEE Access*, vol. 6, pp. 42868–42876, 2018.

[25] Z. Zhao, *High Voltage Technology*, 2nd ed. Beijing, China: China Electric Power Press, 2006.

[26] C. Guo *et al.*, "Influence of electric field non-uniformity on breakdown characteristics in SF_6/N_2 gas mixtures under lightning impulse," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2248–2258, Sep. 2017.

[27] Y. Qiu, J. Che, and M. Zhang, "The homogeneity of SF_6 gas mixture in under high drop condition," *High Voltage Appl.*, vol. 25, no. 3, pp. 12–16, 1989.

[28] J. Zhang, T. Xia, and S. Lai, "Study on the insulation performance of SF_6/N_2 mixed gas in GIL," *High Voltage Appl.*, vol. 52, no. 12, pp. 156–163, 2016.

[29] Wikipedia. (2018). *Kinetic Theory of Gases*. [Online]. Available: https://en.wikipedia.org/wiki/Kinetic_theory_of_gases

[30] R. Ullah, Z. Ullah, A. Haider, S. Amin, and F. Khan, "Dielectric properties of tetrafluoroethane (R134) gas and its mixtures with N_2 and air as a sustainable alternative to SF_6 in high voltage applications," *Electr. Power Syst. Res.*, vol. 163, pp. 532–537, Oct. 2018.

[31] J. Yang, *Gas Discharge*. Beijing, China: Science Press, 1983.

[32] Y. Kieffel, "Characteristics of G_3—an alternative to SF_6," in *Proc. IEEE Int. Conf. Dielectr.*, Jul. 2016, pp. 880–884.

[33] J. Jiao, D. Xiao, S. Zhao, and H. Zhang, "Insulation characteristics for CF_3I-CO_2 gas mixtures with low proportion of CF_3I in extreme non-uniform electric field," *High Voltage Eng.*, vol. 43, no. 3, pp. 772–779, 2016.

[34] S. Xiao, X. Zhang, Y. Han, and Q. Dai, "AC breakdown characteristics of CF_3I/N_2 in a non-uniform electric field," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2649–2656, Oct. 2016.

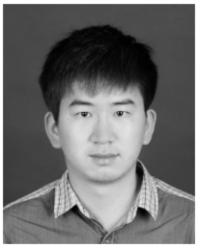
[35] O. Yamamoto, T. Takuma, S. Hamada, Y. Yamakawa, and M. Yashima, "Applying a gas mixture containing c-C_4F_8 as an insulation medium," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 8, no. 6, pp. 1075–1081, Jan. 2002.

[36] D. Xiao and J. Yan, "Application and development of gas insulated transmission line (GIL)," *High Voltage Eng.*, vol. 43, no. 3, pp. 699–707, 2017.

XIAOXING ZHANG was born in Qianjiang, Hubei, China, in 1972. He received the bachelor's and master's degrees from the Hubei Institute of Technology and the Ph.D. degree from Chongqing University. He is currently a Professor with the School of Electric Engineering and Automation, Wuhan University. He is involved in the online monitoring and fault diagnosis of high-voltage electrical insulation equipment, alternative gases of SF_6, the decomposition mechanism of insulating gas SF_6, and the new nano-sensor.

QI CHEN was born in Xiaogan, Hubei, China, in 1995. He is currently pursuing the M.A. degree with the School of Electric Engineering and Automation, Wuhan University. His research interest includes alternative gas of SF_6.

JI ZHANG was born in Dongying, Shandong, China, in 1990. He is currently pursuing the M.A. degree with the School of Electric Engineering and Automation, Wuhan University. His research interest includes alternative gas of SF_6.



YI LI was born in Shangluo, Shanxi, China, in 1994. He received the bachelor's degree in electrical engineering from Wuhan University, Wuhan, China, where he is currently pursuing the Ph.D. degree with the School of Electric Engineering and Automation. His research interests include alternative gas of SF_6 and fault diagnosis of high-voltage electrical insulation equipment.

SONG XIAO was born in Zhangjiakou, Hebei, China, in 1988. He received the B.S. and Ph.D. degrees in electrical engineering from Chongqing University, Chongqing, China, and the Ph.D. degree in plasma engineering from the Université de Toulouse, Toulouse, France. He is currently an Associate Professor with the School of Electric Engineering and Automation, Wuhan University. His research interests include partial discharge online monitoring and gas substituting SF_6.

RAN ZHUO was born in Guiyang, Guizhou, China, in 1986. He received the Ph.D. degree in electrical engineering from Chongqing University. He is currently a Senior Engineer with the Electric Power Research Institute, China Southern Power Grid Co., Ltd. He is mainly involved in high-voltage insulation and power equipment anti-seismic technology.

JU TANG was born in Pengxi, Sichuan, China, in 1960. He received the B.Sc. degree from Xi'an Jiaotong University, Xi'an, China, and the M.Sc. and Ph.D. degrees from Chongqing University, Chongqing, China. He is currently a Professor with the School of Electrical Engineering and Automation, Wuhan University, and the Chief Scientist presiding over the National Basic Research Program of China (973 Program) (2009CB724506). At present, he is involved in high-voltage equipment online monitoring, fault diagnosis, signal processing, simulation analysis, and pattern recognition.

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