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Study on the Dielectric Properties of C_4F_7N/N_2 Mixture Under Highly Non-Uniform Electric Field

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ABSTRACT As an environment-friendly gas insulating medium, C_4F_7N has attracted great attention in recent years due to its excellent environmental protection and insulation performance. However, studies on the insulation performance of C_4F_7N/N_2 gas mixture are not comprehensive at present. In this paper, the breakdown and partial discharge characteristics of the C_4F_7N/N_2 gas mixture under highly non-uniform field were tested using the gas insulation performance test platform. The effects of gas pressure and mixing ratio on the negative partial discharge inception voltage (PDIV−), positive PDIV (PDIV+), and breakdown voltage of the gas mixture were analyzed. The engineering application potential of the C_4F_7N/N_2 gas mixture was also discussed considering the limitation of liquefaction temperature. It is found that an increasing gas pressure or a mixing ratio can effectively improve the insulation performance of the C_4F_7N/N_2 gas mixture. The breakdown properties of a gas mixture for a minimum operating temperature of −25°C at 0.3, 0.4, 0.5, and 0.6MPa can reach 63.4%, 54.6%, 49%, and 56.4% of pure SF_6, respectively, and the PDIV− can reach 80.4%, 66.9%, 62.8%, and 68.8% of pure SF_6, respectively. Relevant results not only reveal the influence of the mixing ratio and pressure on insulation performance of the C_4F_7N/N_2 gas mixture, but also provide significant guidance for its engineering application.

INDEX TERMS C_4F_7N/N_2, SF_6 alternative gas, partial discharge, AC breakdown.

I. INTRODUCTION

Sulphur hexafluoride (SF_6) has great physicochemical properties, excellent insulation and arc extinguishing performance, and is widely used as dielectric medium in the gas insulated equipment (GIE) [1], [2]. However, SF_6 is a very strong greenhouse effect gas with the global warming potential (GWP) 23500 times that of CO_2 [3]–[5]. It is reported that approximately 80% of SF_6 produced worldwide is used in power industry, and its atmospheric content has increased by 20% over the past five years. [6], [7] Moreover, the current equilibrium warming due to SF_6 is 0.004°, with a clear tendency to increase. The Paris agreement signed in 2016 is committed to controlling the global average temperature rise to less than 2°, and a SF_6 emission cut today could contribute 1.5% of this goal [6], [8]. In order to further reduce the use of SF_6, researchers have continued to find an environment-friendly gas with excellent insulation properties to substitute SF_6.

In the past two years, C_4F_7N (2,3,3,3-tetrafluoro-2-(trifluoromethyl)-2-propanenitrile)) has been introduced as a last generation insulation gas. The dielectric strength of C_4F_7N is twice that of pure SF_6, and its GWP is only 2090 [9]. Due to the relatively high liquefaction temperature (−4.7°), it is necessary to mix C_4F_7N with other buffer gas such as CO_2, N_2 or technical air for engineering application [10]. At present, some achievements have been made in the insulation performance of C_4F_7N gas mixture. Kieffel *et al.* [7] tested and found that gas mixtures with 20% C_4F_7N in air or N_2 display dielectric strength comparable to SF_6. Nechmi *et al.* [11], [12] studied the insulation properties of C_4F_7N/CO_2 gas mixture under Alternating Current (AC) and Lightning Impulse (LI) voltage and pointed out that 3.7%C_4F_7N/96.3%CO_2 has the potential to replace SF_6 using in high-voltage (HV) electrical equipment. The effective ionization coefficients and limiting field strength of C_4F_7N/CO_2 gas mixture were also explored. Hopf *et al.* [13] tested the insulation properties of C_4F_7N/CO_2 gas mixture under Direct Current (DC) voltage. Li *et al.* [14] calculated the saturated vapor pressure characteristics C_4F_7N/CO_2 gas mixture. Owens [15] reported that the C_4F_7N/N_2 gas mixture containing 10% and 15% C_4F_7N under 0.5Mpa reaches 80% and 90% of pure SF_6. Li *et al.* [16] tested the insulation and decomposition characteristics of C_4F_7N/N_2 gas mixture under quasi uniform electric fields and found that the insulation performance of 5% C_4F_7N/95% N_2 gas mixture reaches 83.34% of that of SF_6 at 0.15MPa.

At present, there are few reports on the partial discharge (PD) properties of C_4F_7N gas mixture. The manufacture, transportation, installation, operation and maintenance of GIE will inevitably introduce different types of insulation defects within the equipment, which may cause PD [17]. On the one hand, PD will accelerate the further destruction to the internal insulation of the equipment, and eventually lead to insulation failure, which is a potential hidden danger to the operation of GIE. On the other hand, PD can also cause the decomposition of gas insulating medium to produce many by-products, which may change the composition of the gas mixture [18]. Therefore, it is of great significance to explore the partial discharge characteristics of C_4F_7N gas mixture.

In this paper, the gas insulation performance test platform is used to study the partial discharge properties and the power frequency breakdown characteristics of C_4F_7N/N_2 gas mixture under highly non-uniform field. The influence of gas pressure and mixing ratio on the insulation performance of C_4F_7N/N_2 gas mixture is analyzed. And the engineering application potential of C_4F_7N/N_2 gas mixture is also discussed considering the limitation of liquefaction temperature. Relevant results not only reveal the influence of mixing ratio and pressure on insulation performance of C_4F_7N/N_2 gas mixture, but also provide significant guidance for its engineering application.

II. METHOD

A. TEST PLATFORM

Figure 1 shows the schematic diagram of the PD characteristics test platform. The voltage regulator T1 (0-380V) and the experimental transformer T2 (50kVA/100kV) provide the AC high voltage to the circuit, which is applied to the insulation defect via the filter capacitor C1 (0.2μF). The protection resistor R1 (10kΩ) is adopted to limit the current at the breakdown of the electrode gap and protect the entire experimental device. The capacitive voltage divider Ck is used to measure the AC voltage value provided by the transformer. We use the pulse current method recommended by IEC60270 to test the partial discharge characteristics of gas insulating medium [19]. Non-inductance resistor R (50Ω) is used to convert the PD current signal into a voltage signal which is displayed and stored by the digital storage oscilloscope (Tektronix DPO5104B, maximum sampling rate of 10GS/s, analog bandwidth of 1GHz). The test chamber is made of stainless steel (as shown in Figure 2) with a volume of approximately 60L. The needle-plane electrodes (See Figure 2) is built to simulate the highly non-uniform field and the gap distance is set to 5mm for all the tests [20].

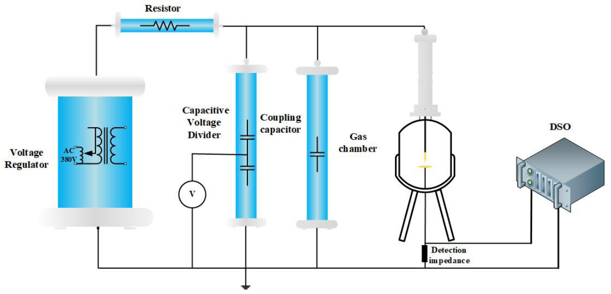


FIGURE 1. Schematic diagram of the PD characteristics test platform.

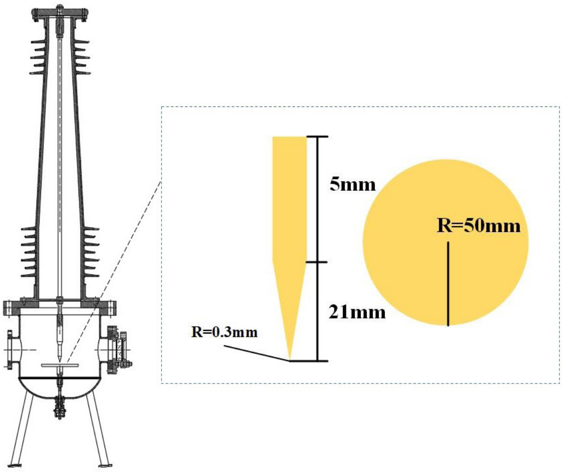


FIGURE 2. Scheme of gas chamber and the needle-plane electrodes.

B. LIQUEFACTION TEMPERATURE OF C_4F_7N/N_2

Liquefaction temperature is an important factor that limits the engineering application of C_4F_7N/N_2 gas mixture. Figure 3 shows the saturated vapor pressure curve of C_4F_7N. It can be seen that the liquefaction temperature of C_4F_7N at 0.1 MPa and 0.2 MPa reaches −4.7°C and 13.06°C, which cannot be directly used in GIE [7]. Thus we select N_2 as the buffer gas to increase the liquefaction temperature. Considering that the liquefaction temperature of C_4F_7N is much higher than that of N_2, if both C_4F_7N and N_2 are regarded as ideal gases, the liquefaction temperature of C_4F_7N/N_2 gas mixture

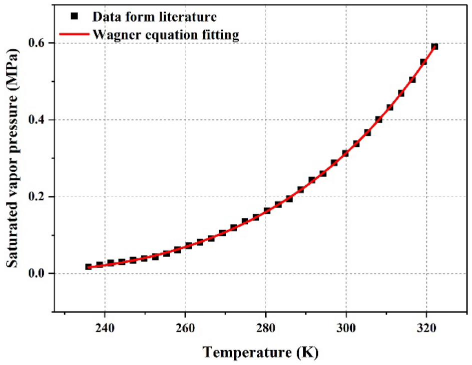


FIGURE 3. Saturated vapor pressure of C_4F_7N.

will be the same as that of C_4F_7N under the corresponding partial pressure.

The Wagner equation obtained by fitting the saturated vapor pressure data given in literature [14] is 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 a C_4F_7N /N_2 gas mixture, $p_c$is the critical pressure (MPa), T is the thermodynamic temperature, and T_c is the critical temperature (K). $T_c = 385.928\text{K}$, $p_c = 2.5028\text{MPa}$, $a = -6.84453$, $b = -1.64783$, $c = 9.26244$, $d = -165.39152$.

According to equation (1), the liquefaction temperature of C_4F_7N/N_2 gas mixture with different mixing ratio at different pressures can be calculated. (See Figure 4)

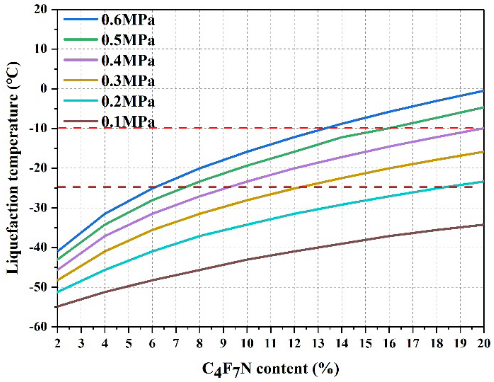


FIGURE 4. Liquefaction temperatures of C_4F_7N/N_2 gas mixture.

At a working temperature of −25°, the content of C_4F_7N in C_4F_7N/N_2 gas mixture should be less than 6% and 12% at 0.6 MPa, 0.3MPa, respectively. For the working temperature of −10°, the optimum content of C_4F_7N should not exceed 13% at 0.6MPa. Considering the liquefaction temperature characteristics of the gas mixture, we studied the partial discharge and AC breakdown characteristics of C_4F_7N/N_2 gas mixture with 2%-12% C_4F_7N at 0.1MPa-0.6MPa in this paper.

C. TEST METHOH

Before the test, the interior of the gas chamber was cleaned using the anhydrous alcohol and then vacuum-pumped. Subsequently, the chamber was charged with N_2 for three times to eliminate the influence of impurity gases. And the C_4F_7N/N_2 gas mixture was injected. We used the pressure-pressure ratios method to achieve correct mixing ratio. The C_4F_7N gas was supplied by 3M ™ China with a purity of 99%. The N_2 and SF_6 were supplied by Wuhan Newred Special Gas Co., Ltd. with a purity of 99.999%.

The AC high voltage was applied to the needle-plane electrode gap to generate the partial discharge, and the waveform of PD signal can be obtained using the high-speed digital acquisition system. Since there is a significant polarity effect in highly non-uniform field, free electrons can easily emit from the needle electrode when it is negative polarity and rapidly move toward the plane electrode, which accumulate a large amount of positive space charge near the needle electrode, and strengthen the field strength near the needle tip. Thus the PD is more likely to occur. When the needle electrode is positive polarity, the positive space charge accumulating in the vicinity of the needle tip weakens the electric field in close proximity to the needle electrode, so that PD does not easily occur.

Figure 5 gives the PD waveform of $4\%C_4F_7N/96\%N_2$ gas mixture at 0.2MPa. When the applied high voltage is in the AC negative half cycle, the needle is negative polarity and PD is easy to occur. Thus the PD generated at the beginning is concentrated in the negative half cycle (see Figure 5 (a)), and the applied voltage was recorded as negative partial discharge inception voltage (PDIV−). With the applied voltage rising further, PD begins to occur in the positive half cycle (see Figure 5 (b)), and the applied voltage at this time is recorded as positive partial discharge inception voltage (PDIV+).

In this paper, the PDIV−, PDIV+, and breakdown voltage of C_4F_7N/N_2 gas mixture were tested five times to avoid accidental errors. The interval between two tests was 5 minutes.

III. RESULTS AND DISCUSSION

A. PDIV OF C_4F_7N/N_2 MIXTURE

1) PDIV− OF C_4F_7N/N_2 MIXTURE

The faults of electrical equipment usually appear as partial discharge at first and its intensification will eventually lead to serious accidents. The partial discharge inception voltage in

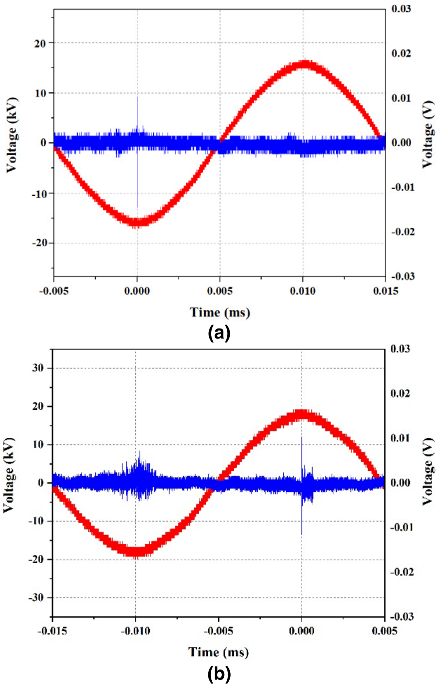
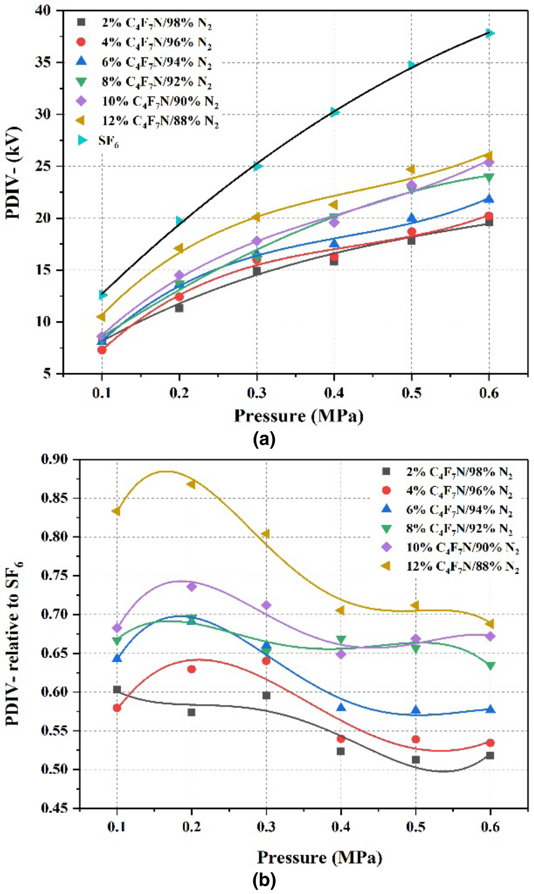


FIGURE 5. Partial discharge waveform of C_4F_7N/N_2 gas mixture (4% $C_4F_7N/96\%N_2$ 0.2MPa) (a) PDIV− signal waveform record, 12kV (b) PDIV+ signal waveform record, 12.5kV.



(a)

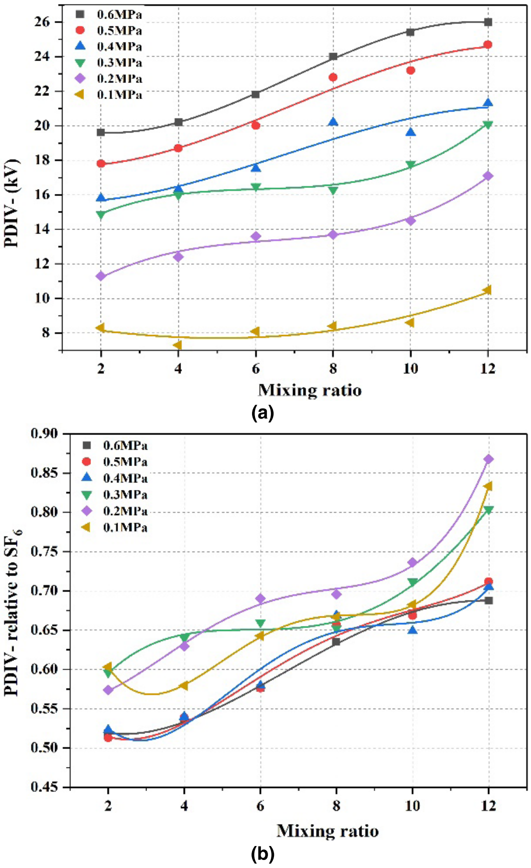
(b)

FIGURE 6. Influence of pressure on PDIV− and relative PDIV− of C_4F_7N/N_2 gas mixture.

the negative half cycle is an important warning sign for faults. Figure 6 shows the variation of PDIV− with gas pressure. The ratio of the insulation performance of C_4F_7N/N_2 gas mixture to SF_6 under the same condition is defined as the relative insulation performance. Figure 6 (b) shows the influence of pressure on the relative PDIV− of C_4F_7N/N_2 gas mixture.

It can be found that the PDIV− of C_4F_7N/N_2 gas mixture containing 2%-12% C_4F_7N is lower than that of SF_6 at the same pressure. The PDIV− of 12%C_4F_7N/88%N_2 gas mixture at 0.3MPa reaches to that of pure SF_6 at 0.2MPa. And the PDIV− of 10% C_4F_7N/ 90%N_2 gas mixture at 0.6MPa is equivalent to pure SF_6 at 0.3MPa. The PDIV− of the gas mixture shows a saturation growth trend with the increase of pressure. When the gas pressure is lower than 0.3MPa, its increase rate is higher than that of 0.4 - 0.6MPa.

The relative PDIV− of gas mixture presents three stages with the change of pressure. When the gas pressure is lower than 0.2MPa, increasing pressure can effectively improve the relative PDIV−. And the relative PDIV− of gas mixture with 4%, 6%, 8%, 10%, and 12% C_4F_7N at 0.2MPa is higher than other conditions. As the gas pressure increases further, the relative PDIV− of C_4F_7N/N_2 mixture decreases significantly and reaches a minimum value at 0.4 MPa and tends to be stable within the range of 0.4MPa-0.6MPa. Moreover, it can be found that the relative dielectric strength of the gas mixture with 8% C_4F_7N has small fluctuation at 0.1-0.6 MPa.



(a)

(b)

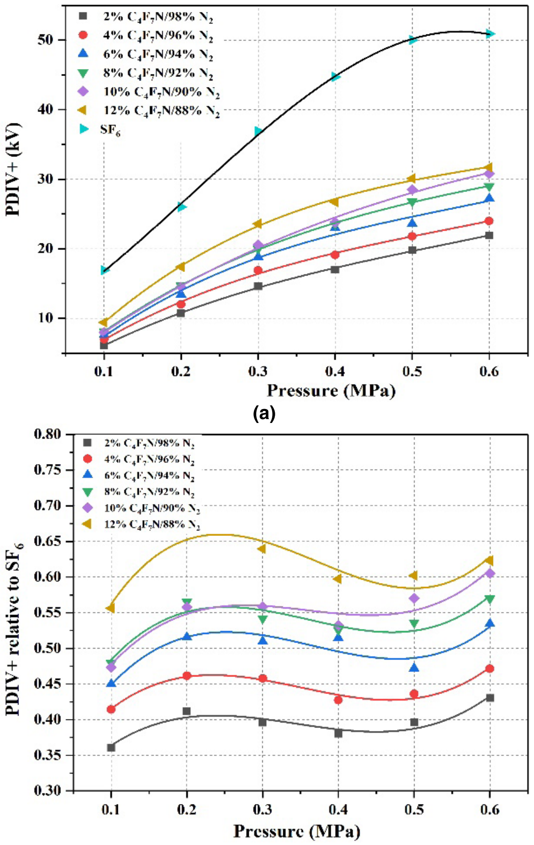
FIGURE 7. Influence of mixing ratio on PDIV− and relative PDIV− of C_4F_7N/N_2 gas mixture.

The PDIV− of C_4F_7N/N_2 gas mixture increases with mixing ratio (C_4F_7N content), as shown in Figure 7. The relative PDIV− of the gas mixture containing 6%-10% C_4F_7N at 0.1-0.3MPa is basically identical, then increases significantly when the C_4F_7N content reaches to 12%. The PDIV− of 12%C_4F_7N/88%N_2 at 0.3MPa, 0.2MPa reaches to 80% and 86% of pure SF_6. Therefore, it is recommended to use the mixture with the C_4F_7N content more than 10% for low gas pressure equipment. This solution can take both the liquefaction temperature limits and insulation performance requirements for engineering applications into account.

The PDIV− shows a saturation growth trend with the increase of mixing ratio at high pressure (0.4MPa - 0.6MPa). The relative PDIV− of gases with 4%-8% C_4F_7N increases with the mixing ratio, and tends to be saturated when the C_4F_7N content exceeds 10%. The PDIV− of 10%C_4F_7N/90%N_2 at 0.5MPa, 0.6MPa reaches to 66.9% and 67.2% of pure SF_6. And it is recommended to use the gas with 8%-10% C_4F_7N for high gas pressure equipment.

2) PDIV+ OF C_4F_7N/N_2 MIXTURE

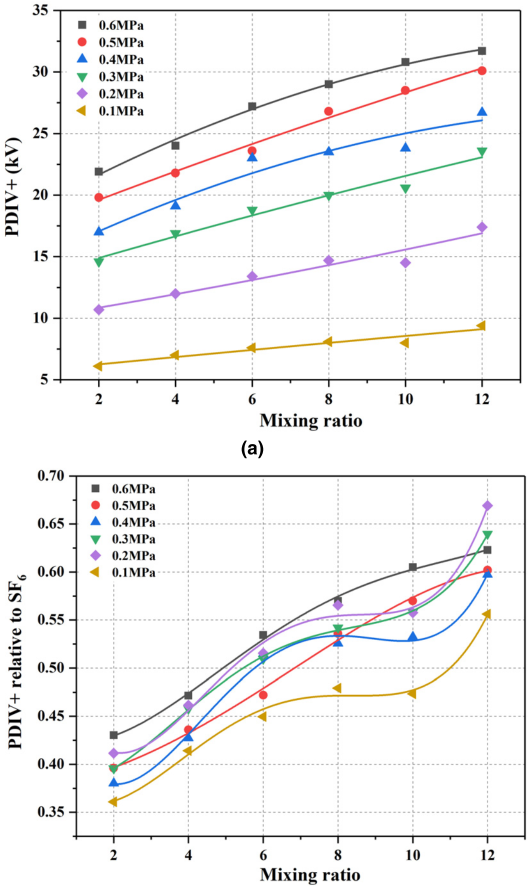
As the applied voltage amplitude increases, the PD signal begins to appear in the AC positive half cycle. The value



(a)

(b)

FIGURE 8. Influence of pressure on PDIV+ and relative PDIV+ of C_4F_7N/N_2 gas mixture.



(a)

(b)

FIGURE 9. Influence of mixing ratio on PDIV+ and relative PDIV+ of C_4F_7N/N_2 gas mixture.

of PDIV+ is between the PDIV− and breakdown voltage, which is an important physical quantity of streamer discharge and marks the critical stage of gas insulation deterioration. The detection and analysis of PDIV+ helps to further excavation the insulation performance of C_4F_7N/N_2 gas mixture.

Figure 8 shows the variation of PDIV+ with gas pressure. It can be found that PDIV+ increases with pressure and the growth rate slows down at higher pressure. The relative PDIV+ of gas mixture is lower than that of PDIV− under the same conditions. For example, the PDIV− of $12\%C_4F_7N/88\%N_2$ gas mixture is 86.8% of SF_6 at 0.2 MPa, while the PDIV+ is only 66.9% of SF_6.

The change of relative PDIV+ with pressure is shown in Figure 8 (b). The relative PDIV+ of C_4F_7N/N_2 gas mixture reaches to the highest value at 0.2 MPa, and then decreases with gas pressure. When the pressure reaches to 0.6 MPa, the relative PDIV+ increases again. Therefore, for the medium and low gas pressure equipment, the relative insulation performance of C_4F_7N/N_2 gas mixture at 0.2MPa is the best. As to the high pressure equipment, the relative insulation performance of C_4F_7N/N_2 gas mixture at 0.5MPa - 0.6MPa is superior.

The influence of mixing ratio on PDIV+ is given in Figure 9. We can find that the PDIV+ of C_4F_7N/N_2 gas mixture showed a linear saturated increase trend with mixing ratio. When the pressure is lower than 0.4 MPa, the relative PDIV+ of the gas mixture with C_4F_7N content less than 6% increases with the mixing ratio. The relative PDIV+ of gas mixture with 6% −10% C_4F_7N remains stable, and increases when the C_4F_7N content exceeds 10%. For medium and low gas pressure applications, increasing the mixing ratio can effectively enhance the insulation performance of C_4F_7N/N_2 gas mixture. Under high pressure conditions (0.5-0.6 MPa), the relative PDIV+ of C_4F_7N/N_2 gas mixture showed a linear saturated increase trend with mixing ratio.

B. BREAKDOWN OF C_4F_7N/N_2 MIXTURE

In order to further explore the insulation performance of C_4F_7N/N_2 gas mixture, we tested the AC breakdown voltage under highly non-uniform field. Figure 10 shows the influence of pressure on the breakdown voltage of C_4F_7N/N_2 gas mixture.

The breakdown voltage of C_4F_7N/N_2 gas mixture under highly non-uniform field increases with gas pressure. The breakdown voltage of a $12\%C_4F_7N/88\%N_2$ mixture at 0.4 MPa is equivalent to pure SF_6 at 0.2MPa. In addition, the relative dielectric strength of the C_4F_7N/N_2 gas mixture reaches its maximum value at 0.3 MPa or 0.2 MPa, and decreases at higher pressure. That is, the relative insulation

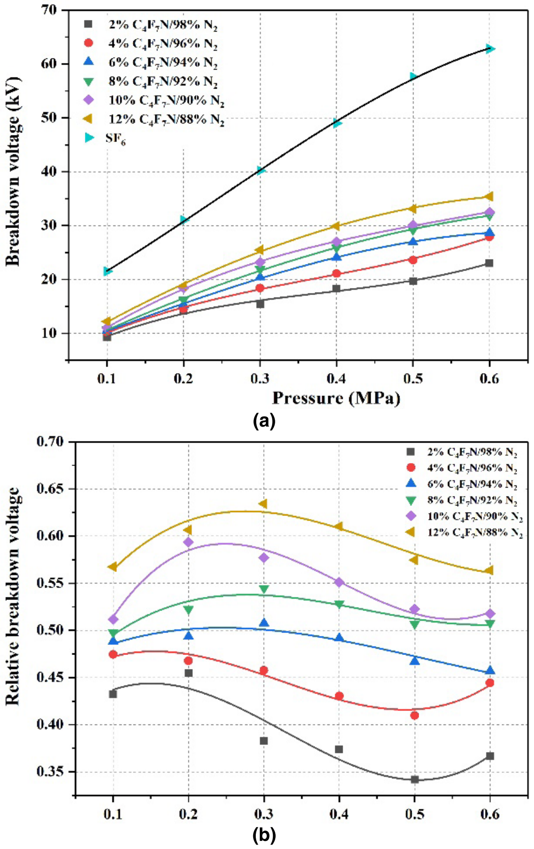


FIGURE 10. Influence of pressure on breakdown voltage of C_4F_7N/N_2 gas mixture.

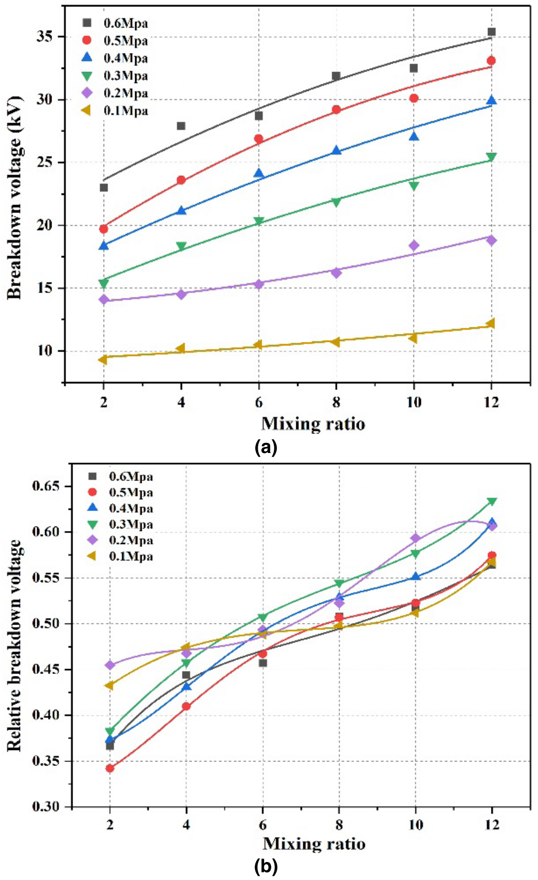


FIGURE 11. Influence of mixing ratio on breakdown voltage of C_4F_7N/N_2 gas mixture.

performance of C_4F_7N/N_2 gas mixture at high pressure is lower than that of low pressure.

The effect of the mixing ratio on the breakdown characteristics of C_4F_7N/N_2 gas mixture is shown in Figure 11. The breakdown voltage increases with the mixing ratio and the relative breakdown voltage of C_4F_7N/N_2 gas mixture at high pressure (0.5-0.6MPa) is lower than low pressure.

C. DISCUSSION

1) INFLUENCE MECHANISM OF PRESSURE AND MIXING RATIO ON INSULATION OF C_4F_7N/N_2

According to the above test results, we can find that the insulation performance of C_4F_7N/N_2 gas mixture can be effectively improved by increasing the gas pressure or mixing ratio, but the influence mechanism is different.

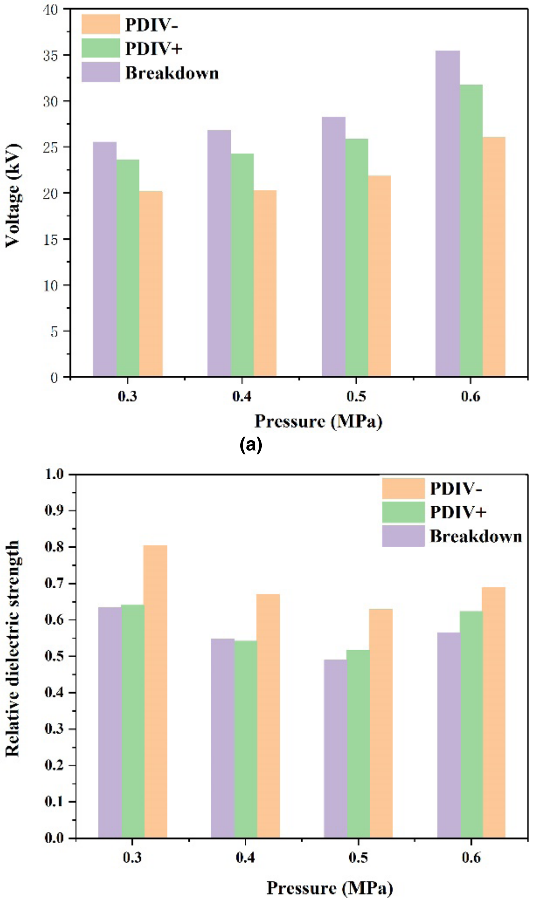
The increase of pressure actually increases the density of gas mixture. Thus the mean free path of electrons in the mixture is shortened, and electrons cannot accumulate kinetic energy easily. As a result, the probability of impact ionization is reduced. The insulation performance at high pressure is better than low pressure. Moreover, the space charge region formed by PD improves the electric field distribution in the gap and inhibits the development of the streamer discharge to a certain extent, which can be described as the restricting or stabilizing effect. When the pressure is low, the PDIV increases with the gas pressure, and the stabilizing effect of space charge makes the breakdown voltage significantly higher than the PDIV. While when the gas pressure reaches a certain value, the migration and diffusion of space charge is suppressed, the corona layer produced by PD is compressed, and the stabilizing effect of space charge is reduced, so that the breakdown voltage rise rate is significantly reduced, as shown in Figure 10 (a).

Both SF_6 and C_4F_7N are strongly electronegative gases, and their molecular structure contains F atoms with strong electronegativity. Therefore, C_4F_7N can easily capture electrons and becomes negative ions, thereby the ability of electron impact ionization is weakened. In addition, the molecular volume and the collision cross-section of C_4F_7N is large, thus the free path of electrons is shortened. With the increase of the mixing ratio, the content of C_4F_7N increases and the insulation performance of the gas mixture is enhanced.

As a whole, the insulation performance of C_4F_7N/N_2 gas mixture can be enhanced by increasing the content of C_4F_7N or gas pressure, but the two schemes are all restricted by the liquefaction temperature condition. Therefore, the engineering application of C_4F_7N/N_2 needs to meet the relevant liquefaction temperature requirements firstly, and then select the optimal mixing ratio and pressure reasonably.

TABLE 1. **Dielectric properties of C_4F_7N/N_2 gas mixture (a minimum operating temperature of −25°C).**

Pressure	Gas mixture	PDIV-	PDIV+	Breakdown
0.3MPa	$12\%C_4F_7N/88\%N_2$	26	31.7	35.4
0.4MPa	$9\%C_4F_7N/91\%N_2$	21.8	25.8	28.2
0.5MPa	$7.5\%C_4F_7N/92.5\%N_2$	20.2	24.2	26.8
0.6MPa	$6\%C_4F_7N/94\%N_2$	20.1	23.6	25.5



(a)

(b)

FIGURE 12. **Dielectric properties of C4F7N/N2 gas mixture (a minimum operating temperature of −25°C).**

2) APPLICATION POTENTIAL OF C_4F_7N/N_2

According to the liquefaction temperature calculation results, the content of C_4F_7N in the gas mixture at 0.2-0.6MPa should not exceed 6%, 7.5%, 9%, 12%, and 18% considering the working temperature of −25°. For medium-voltage (MV) electrical equipment (gas pressure usually less than 0.2MPa), it is recommended to improve the insulation performance by increasing the mixing ratio. Literature [7] pointed out that the insulation performance of gas mixture containing 18%-20% C_4F_7N achieves a dielectric strength of pure SF_6. Thus C_4F_7N/N_2 gas mixture has the potential to completely replace SF_6 in MV electrical equipment.

For high pressure gas insulated equipment, the minimum operating temperature limits the gas pressure and mixing ratio. Table 1 and Figure 12 gives the PDIV−, PDIV+, and breakdown voltage of C_4F_7N/N_2 gas mixture for a minimum operating temperature of −25°C.

It can be found that the breakdown voltage of C_4F_7N/N_2 gas mixture for a minimum operating temperature of −25°C at 0.3 MPa, 0.4 MPa, 0.5 MPa, and 0.6 MPa (highly non-uniform field) is about 63.4%, 54.6%, 49%, and 56.4% of pure SF_6; And the PDIV− reaches 80.4%, 66.9%, 62.8% and 68.8% of pure SF_6.

IV. CONCLUSION

In this paper, the breakdown and partial discharge characteristics of C_4F_7N/N_2 gas mixture under highly non-uniform field were tested using the gas insulation performance test platform. The effects of gas pressure and mixing ratio on the PDIV−, PDIV+ and breakdown voltage of gas mixture were analyzed. The engineering application potential of C_4F_7N/N_2 gas mixture was also discussed considering the limitation of liquefaction temperature, the following conclusions can be summarized:

1) The PDIV−, PDIV+, and breakdown voltage of C_4F_7N/N_2 gas mixture with 2%-12% C_4F_7N increases with the gas pressure, but the dielectric strength is weaker than that of pure SF_6under the same pressure.
2) The insulation performance of C_4F_7N/N_2 gas mixture increases with the mixing ratio. The relative insulation performance of gas mixture at high pressure (0.5-0.6 MPa) shows a saturation growth trend with the mixing ratio.
3) The breakdown voltage of C_4F_7N/N_2 gas mixture for a minimum operating temperature of −25°C at 0.3 MPa, 0.4 MPa, 0.5 MPa, and 0.6 MPa (highly non-uniform field) is about 63.4%, 54.6%, 49%, and 56.4% of pure SF_6; And the PDIV− reaches 80.4%, 66.9%, 62.8% and 68.8% of pure SF_6.
4) The insulation performance of C_4F_7N/N_2 gas mixture is sensitive to non-uniformity of electric field, especially at high pressure conditions. Thus the structure of GIE using C_4F_7N/N_2 gas mixture should be further optimized to avoid the occurrence of non-uniformity electric field.

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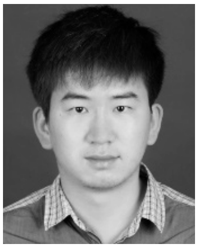

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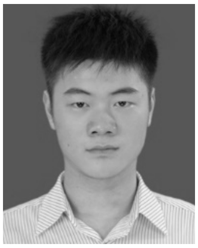

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