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AC Breakdown Characteristics of c-C_4F_8/N_2 Gas Mixtures in an Extremely Non-Uniform Electric Field

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Abstract: Octafluorocyclobutane (c-C_4F_8) is one of the environmentally friendly gases with the potential to replace SF_6. In this paper, the AC breakdown characteristics of c-C_4F_8/N_2 mixture in an extremely non-uniform electric field were studied; the effects of the gas pressure, electrode distance, and c-C_4F_8 volume fraction on the breakdown voltage were analyzed; and the feasibility of replacing SF_6 with c-C_4F_8/N_2 was verified. The results show that the breakdown voltage of c-C_4F_8 /N_2 increases with an increase in pressure, electrode spacing, and volume fraction of c-C_4F_8 in an extremely non-uniform electric field. Under the same conditions, the breakdown voltage of 20%c-C_4F_8/80%N_2 is 46–90% that of 20%SF_6/80%N_2. When the pressure is 0.3 MPa, the 20%c-C_4F_8/80%N_2 breakdown voltage can reach over 57% that of SF_6. Taking into consideration the environment, liquefaction temperature, and insulation strength, 20%c-C_4F_8/80%N_2 may replace SF_6 used for medium- and low-voltage equipment.

Keywords: gas insulation; alternative gas of SF_6; breakdown voltage; extremely non-uniform electric field; c-C_4F_8/N_2

1. Introduction

Sulfur hexafluoride (SF_6) is widely used in power systems and electrical equipment owing to its high insulation level and arc-extinguishing capacity [1,2]. However, the non-homogeneity of an electric field, the conducting particles, and the surface roughness of the electrode all have a significant influence on the dielectric strength of SF_6 during use [3–5]. Above all, SF_6 is a potent greenhouse gas whose global warming potential (GWP) is 23,900 times that of CO_2, and whose life expectancy is 3200 years in the atmosphere, which causes a severe greenhouse effect [6,7]. Therefore, in the Kyoto protocol adopted by Japan on December 1997, SF_6 was listed as one of six gases requiring global regulation [8]. Considering the environment, it has become an inevitable tendency to find a new environment-friendly gas to replace SF_6.

Thus, many gases with high insulating strength have been concentrated on by researchers to replace SF_6, such as octurobutane (c-C_4F_8), trifluoroiodomethane(CF_3I), heptafluorobutyronitrile (C_4F_7N) and trifluorovinyl ether ($C_5F_{10}O$). However, the boiling points of C_4F_7N and $C_5F_{10}O$ are high, which restrict the use for low temperature environments. Although CF_3I has low toxicity, the decomposition product of CF_3I contains iodine, and the effect of iodine on breakdown is not clear [9], while c-C_4F_8 is an electronegative gas with stable chemical properties, and displays non-toxicity, non-combustibility, and non-ozone effects [10]. The breakdown voltage of c-C_4F_8 is 1.3 times of SF_6 under a uniform electric field, while the GWP of c-C_4F_8 is 8700, which is about 1/3 of SF_6, so the impact on the environment is much smaller than that of SF_6 [11,12]. c-C_4F_8 mixed gas was listed as an insulating gas for future long-term research at the 1997 technical conference of the National Association of Standards and Technology [13]. Owing to the high liquefaction temperature of c-C_4F_8 gas, it cannot be directly used in electrical equipment, and buffer gases such as N_2 or CO_2 are often added in use. So far, researchers have conducted many studies on the electrical properties of c-C_4F_8 mixtures [6,14]. Xiao et al. investigated the AC breakdown characteristics of c-C_4F_8/N_2 and c-C_4F_8/CO_2 under a slightly non-uniform electric field, analyzed the breakdown products, and obtained the synergetic coefficients of mixed gases under different volume fractions. Results indicate that c-C_4F_8/N_2 and c-C_4F_8/CO_2 can be used as an alternative gas to SF_6 under certain conditions [15,16]. Xing et al. studied the partial discharge characteristics of a c-C_4F_8/N_2 mixed gas, and demonstrated the feasibility of substituting c-C_4F_8/N_2 for SF_6 in terms of the liquid temperature, environmental influence, and partial discharge characteristics [17]. Li et al. analyzed the decomposition products of a c-C_4F_8/N_2 mixed gas under typical faults such as local overheating, a partial discharge, spark, and arc discharges, and confirmed that the breakdown products of a c-C_4F_8/N_2 mixture under several common faults are less toxic, thus c-C_4F_8/N_2 can be used as an alternative to SF_6 [18].

Thus far, researchers have studied the insulation properties of a c-C_4F_8/N_2 mixture under a uniform and slightly non-uniform electric field. However, in practical application, owing to the limitation of processing technology, burrs or suspended impurity particles are present in gas-insulated high-voltage equipment, which will lead to a distortion of their local electric field. Therefore, it is also particularly important to investigate the breakdown characteristics of the gas insulated under an extremely non-uniform electric field. In this paper, a discharge device was established and an AC test platform was set up. Based on the use conditions, the volume fraction of c-C_4F_8 in the test was determined, and the breakdown voltages of c-C_4F_8/N_2 under different pressures, electrode distances, and volume fractions of c-C_4F_8 were tested. The trend of breakdown voltage changes with pressure, electrode distance and the volume fraction of c-C_4F_8 was then analyzed. The feasibility of replacing SF_6 with c-C_4F_8/N_2 is discussed.

2. Experimental Setup

2.1. Experimental Circuit

The experimental circuit adopted in this paper is shown in Figure 1. The adjustable range of the voltage regulator was 0–220V and the transformer was a YWDT-15kVA/150kV model (Yingkou Jingcheng Special Transformer Co. Ltd., Yingkou, China). Resistance in the circuit was 10 kΩ, used to reduce the output current and protect the transformer. The current of the relay in the voltage regulator was set at 2.1 A. The circuit was arranged so that when the gas broke down, the current reached a set value, the relay opened, and the breakdown voltage measured. The values of capacitor C_1 and C_2 were, respectively, 309 pF and 0.307 μF [19,20]. Before the test, the discharge device was vacuumed, and then filled with mixed gas. During the test, the voltage was manually increased until breakdown of the mixed gas. When the voltage is much less than the breakdown voltage, the boost speed of the voltage is high; conversely, the boost speed slows when the voltage is close to the breakdown voltage. After five duplicate tests, the average value was taken as the breakdown voltage. The interval between the tests was 5 min.

The discharge device is shown in Figure 2. As the pressure of the insulating gas used is generally 0.3–0.5 MPa [7,21], the discharge device must safely withstand a pressure of at least 0.5 MPa. The cavity of the discharge device was enclosed by a stainless steel 304 seamless steel tube with a diameter of 300 mm, height of 470 mm, and thickness of 10 mm. The upper and lower closure plates were made of stainless steel 304 with a thickness of 20 mm. In addition, two observation windows with a diameter of 50 mm were placed on both sides of the cavity to observe the experimental phenomena. The observation windows were made of a stainless steel flange and tempered glass. A high-voltage electrode was introduced through high-voltage bushing.

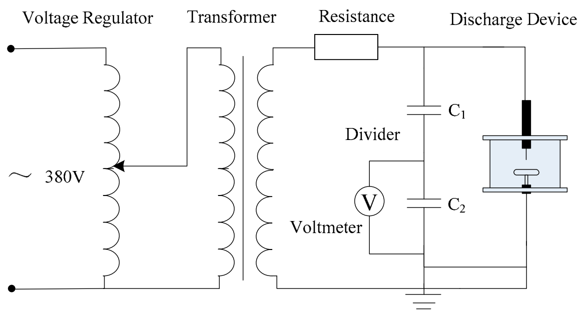

Figure 1. Experiment circuit.

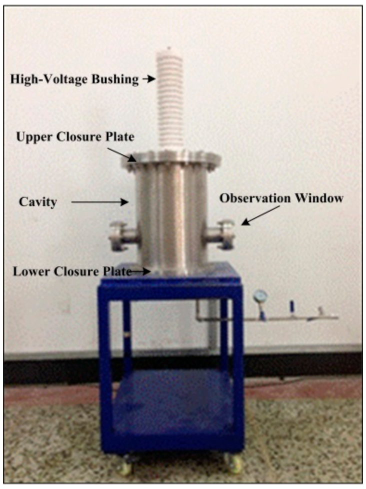

Figure 2. Photograph of discharge device.

2.2. Electrode and Electric Field Simulation

In this study, a needle-plate electrode was used to generate an extremely non-uniform electric field. The electrode distance ranged from 0 to 20 mm. The diameter of the plate electrode was 140 mm, the thickness was 25 mm, and the chamfer radius was 8 mm. The diameter of the needle electrode was 5 mm, the length was 50 mm, the length of the tip was 5 mm, and the tip curvature radius was about 0.15 mm; in addition, both needle-plate electrodes were made of brass. Because the discharge will lead to material loss at the tip and increase the curvature radius of the electrode, the needle electrode should be regularly replaced.

During the test, the electrode distances were 5, 10, 15, and 20 mm. Here we calculate the non-uniformity coefficients f under different electrode distances with the following expression [20,22]:

$$f = \frac{E_{max}}{E_{av}} \quad (1)$$

$$E_{av} = \frac{U}{d} \quad (2)$$

where E_{max} is the maximum electric field strength (V/m), E_{av} is the average electric field strength (V/m), U is voltage applied to the electrode (V), and d is the electrode distance (m).

We used COMSOL software to simulate the electric field distribution, and obtained the E_{max} between the needle-plates with different electrode distances. The simulation result when the electrode distance was 20 mm is shown in Figure 3.

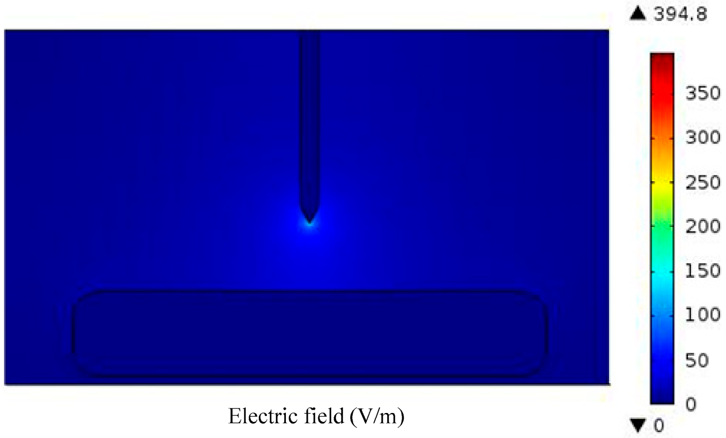

Figure 3. Electric field simulation of needle-plate electrode at 20 mm.

Based on the simulation results, the non-uniformity coefficients calculated under different electrode distances are shown in Table 1.

Table 1. Non-uniformity coefficients under different electrode distances.

Electrode gap /mm	5	10	15	20
Non-uniformity coefficients	4.2	5.75	6.9	7.9

It can be seen from the calculation results that the non-uniformity coefficients of the electric field calculated at different electrode distances are all greater than 4 [22], and thus the distribution of the electric field between the inter-electrode conforms to the requirement of an extremely non-uniform electric field.

2.3. Volume Fraction of Mixture

$c\text{-}C_4F_8$ and N_2 used were manufactured by Huate Gas Co., Ltd (Foshan, China), and the prices were USD 75.00 and USD 0.70 per kilogram, respectively. The purity of $c\text{-}C_4F_8$ and N_2 in the experiment was above 99.9%. The liquefaction temperature of N_2 is −195.8 °C, which is far lower than $c\text{-}C_4F_8$ (−8 °C). In the test, the mixture was set at 0.5 MPa and −10 °C without liquefaction. Actually, the liquefaction temperature of the mixture should be lower than the operating temperature. The maximum volume fraction of $c\text{-}C_4F_8$ in the mixture can be calculated through the following formula [23]:

$$T_{mb} = \frac{T_b}{1 - \ln(10kP)/10.5} \tag{3}$$

where T_{mb} is the liquefaction temperature of a mixed gas (K), T_b is the liquefaction temperature value of $c\text{-}C_4F_8$ (K), P is the gas pressure (MPa), and k is the volume fraction of $c\text{-}C_4F_8$ when the gas pressure is P.

It can be determined through Equation (3) that the volume fraction of $c\text{-}C_4F_8$ in a mixed gas is not more than 20%. In the test, the pressure ranged from 0.1 to 0.5 MPa; the testing step length was 0.05 MPa; the volume fractions of $c\text{-}C_4F_8$ were 5%, 10%, 15%, and 20%; the accuracy of mixed gases was ±1%; and the experiment was conducted at 20 °C.

3. Results and Discussion

3.1. Breakdown Voltages of c-C_4F_8/N_2 Mixture Changes with Pressure

The AC breakdown characteristics of c-C_4F_8/N_2 in an extremely non-uniform electric field were obtained from the test, and the breakdown voltages of the gas mixture changed with the gas pressure are shown in Figure 4.

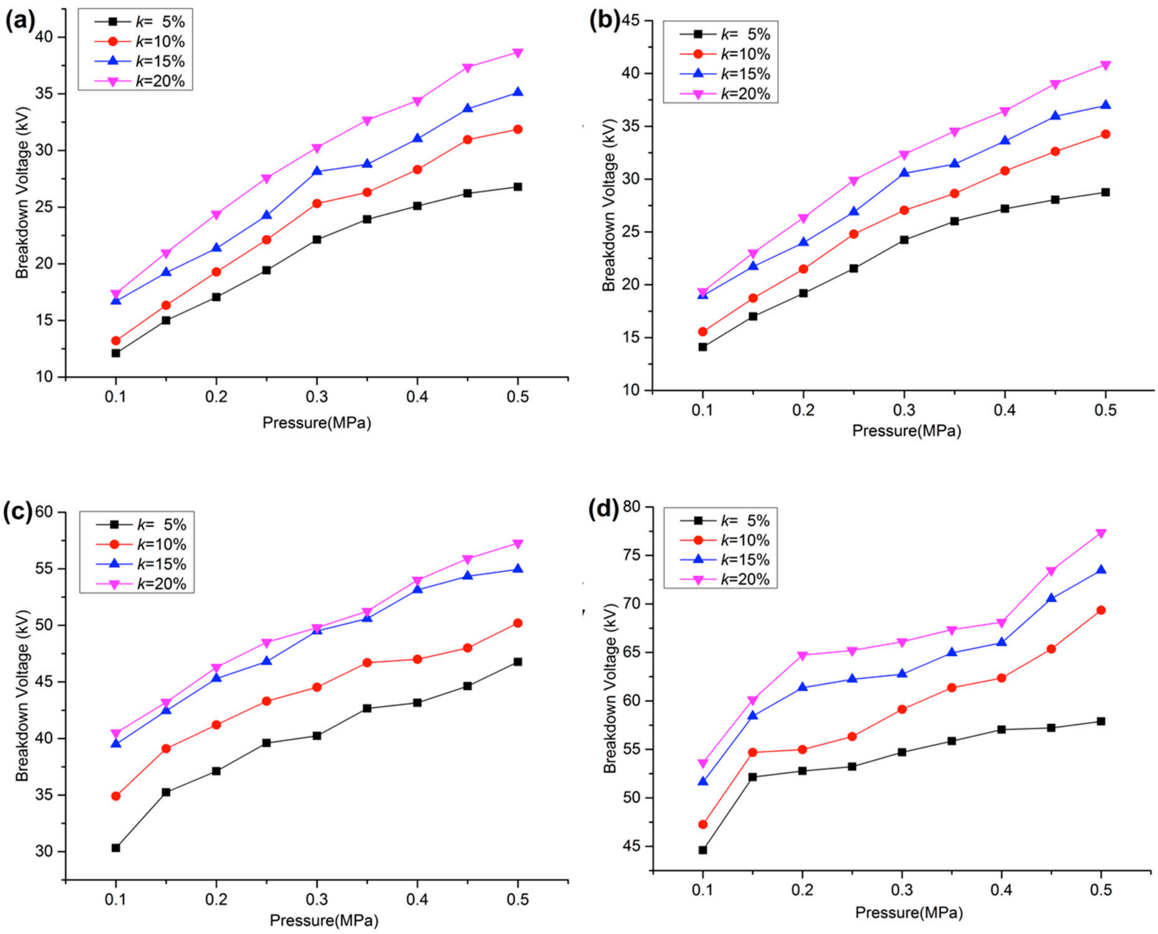

Figure 4. The breakdown voltages of the mixture varying with pressure: electrode distance *d* of (**a**) 5, (**b**) 10, (**c**) 15, and (**d**) 20 mm.

It can be seen from Figure 4 that the pressure has a significant impact on the breakdown voltage. On the whole, the AC breakdown voltages of c-C_4F_8/N_2 mixture increase with the increase in pressure. When the gaps between the electrodes are 5, 10, or 15 mm, the AC breakdown voltage shows the same increase trend as the change in pressure. When the electrode distance is 5 or 10 mm, the breakdown voltage of the gas at a pressure of 0.5 MPa increases approximately two-fold to 0.1 MPa, whereas when the electrode distance is 15 mm, the breakdown voltages increases by about 1.5-fold. The reason why the breakdown voltages increase with pressure is because, as the pressure increases, the number of molecules per volume increases, which shortens the free path of the electrons. The amount of energy accumulated by the electrons decreases in the free path, thus affecting the development of an electron avalanche. At the same time, c-C_4F_8 is an electronegative gas, with a relatively large cross-section in the low energy region, and can attract low-energy electrons, thereby generating negative ions and further increasing the breakdown voltage. When the electrode distance is 20 mm, the breakdown voltages showed different trends with the pressure. Under a pressure of 0.15 MPa, the breakdown voltage increases rapidly, and breakdown voltages between 0.15 and 0.40 MPa increase slowly. When the pressure exceeds 0.4 MPa, the breakdown voltages increases sharply, that is, a "hump" appears. This phenomenon exists in the breakdown of mixed gases such as SF_6, C_3F_8, and CF_3I [24]. The main reason for this is that a stable corona can be formed at the tip of the needle in an extremely non-uniform electric field, and the electric field distribution around the needle electrode can be improved to further increase the breakdown voltages; thus, the breakdown voltage is higher when the pressure is 0.15 MPa. However, as the pressure increases further, the diffusion motion of the space charge decreases, the size of the corona decreases, the effect on the improvement of the electric field diminishes, and the breakdown voltage increases slowly.

3.2. Breakdown Voltages of c-C_4F_8/N_2 Mixture Varying with Electrode Distance

The breakdown voltage of c-C_4F_8/N_2 gas varied with the electrode distance, as shown in Figure 5.

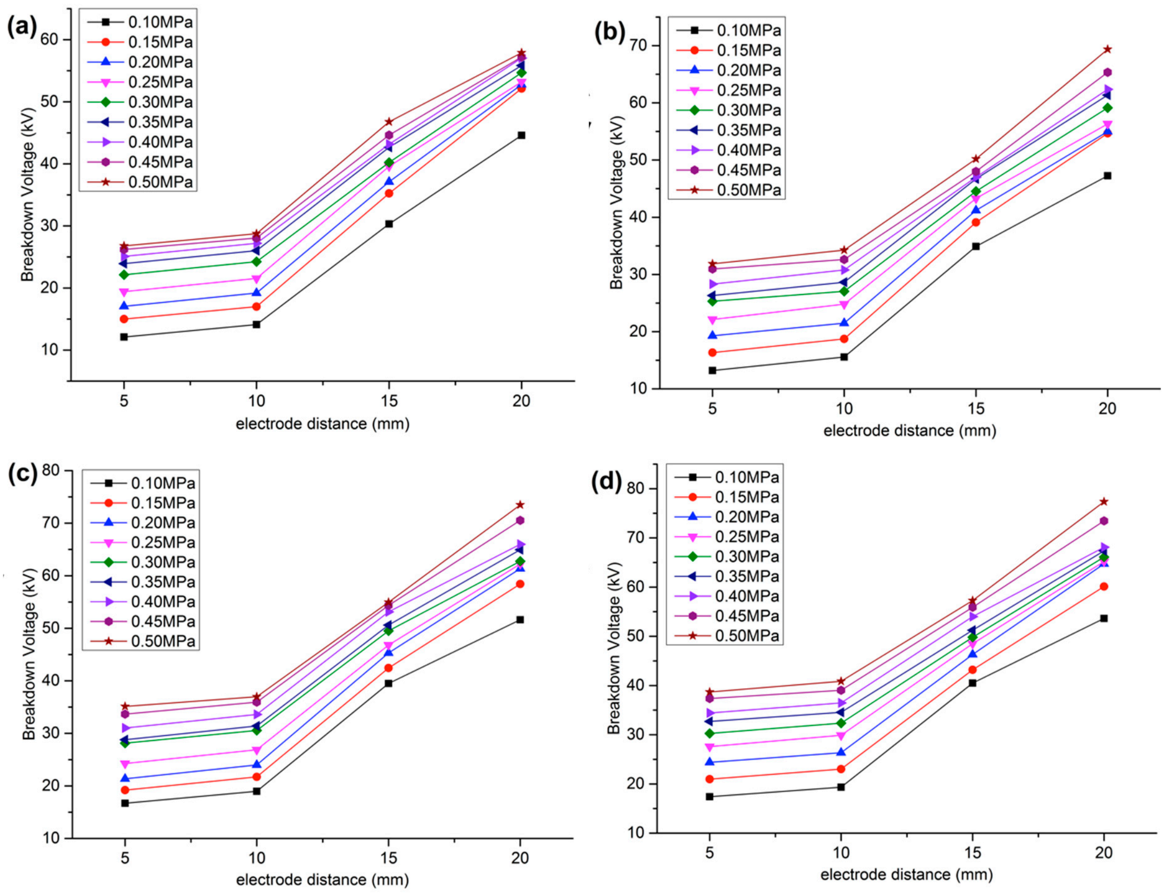

Figure 5. The breakdown voltage of c-C_4F_8/N_2 gas varying with the electrode distance for *k* of (**a**) 5%, (**b**) 10%, (**c**) 15%, and (**d**) 20%.

As shown in Figure 5, c-C_4F_8/N_2 shows the same growth trend with the change in electrode distance under a different volume fraction. When the electrode distance is 10 mm, no significant improvement is shown when compared with the breakdown voltage of 5 mm. When the electrode distance is larger than 10 mm, the breakdown voltage significantly increases in a linear fashion.

3.3. Breakdown Voltages of c-C_4F_8/N_2 Mixture Varying with Volume Fraction

When the electrode distance is 5 or 15 mm, the breakdown voltages of the c-C_4F_8/N_2 mixture change with the volume fraction *k* of c-C_4F_8, as shown in Figure 6.

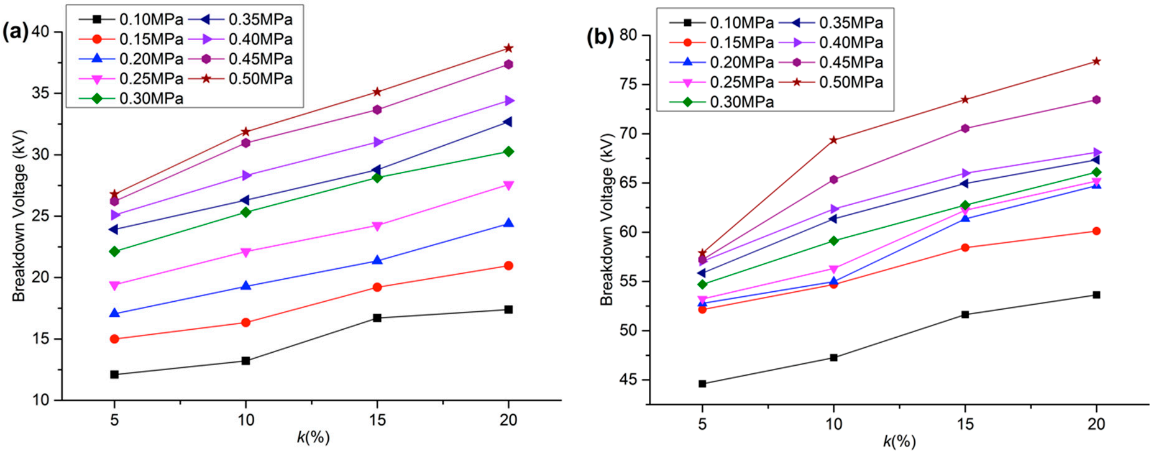

Figure 6. The breakdown voltage of c-C_4F_8/N_2 gas varying with the volume fraction for *d* of (**a**) 5 and (**b**) 15 mm.

According to Figure 6, as the volume fraction of c-C_4F_8 increases, the dielectric strength of c-C_4F_8/N_2 increases. When the electrode distance is 5 mm, c-C_4F_8/N_2 increases nearly linearly with the increase in the volume fraction of c-C_4F_8. When the electrode distance is 15 mm, the pressure is 0.45 and 0.50 MPa; in addition, the volume fraction *k* increases from 5% to 10%, and the breakdown voltage significantly improves. The reason that breakdown voltage increases is that, with the increase in volume fraction, the probability of c-C_4F_8 attracting electrons increases, and the electron avalanche development slows, resulting in an increase in the breakdown voltage. It can be seen from this trend that if the volume fraction of c-C_4F_8 is less than 20%, the breakdown voltage of c-C_4F_8/N_2 can be increased through an increase in the volume fraction of c-C_4F_8.

3.4. Feasibility of Replacing SF_6/N_2 with c-C_4F_8/N_2

To verify the insulation level of c-C_4F_8/N_2 under an extremely non-uniform electric field, the breakdown voltages of c-C_4F_8/N_2 were compared with those of SF_6 and 20%SF_6/80%N_2 under the same experimental conditions. The breakdown voltages of SF_6 and 20%SF_6/80%N_2 were taken from [23], and the comparison results are shown in Figure 7.

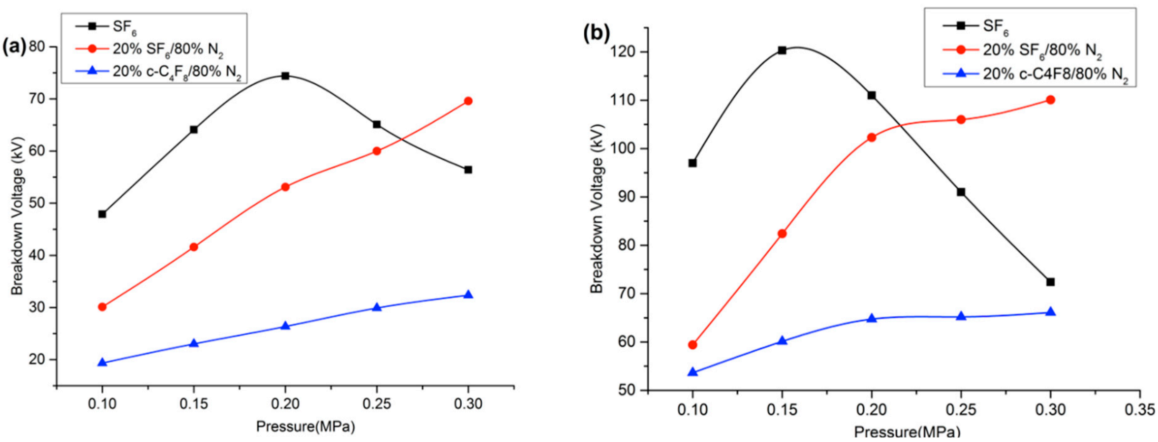

Figure 7. Comparisons of the breakdown voltages of SF_6, c-C_4F_8/N_2, and 20%SF_6/80%N_2 in an extremely non-uniform electric field for *d* of (**a**) 10 and (**b**) 20 mm.

It can be seen from Figure 7 that when the electrode distance is 10 or 20 mm, on the whole the breakdown voltages of 20%c-C_4F_8/80%N_2 are lower than those of SF_6 and 20%SF_6/80%N_2. When the electrode distance is 10 mm, the breakdown voltage of 20%c-C_4F_8/80%N_2 is 46–64% that of 20%SF_6/80%N_2. At 0.3 MPa, the breakdown voltage of 20%c-C_4F_8/80%N_2 is 57% that of SF_6. When the electrode distance is 20 mm, the breakdown voltage of 20%c-C_4F_8/80%N_2 is 60–90% that of 20%SF_6/80%N_2. At 0.3 MPa, the 20%c-C_4F_8/80%N_2 breakdown voltage is 66.1 kV, or 91% of the breakdown voltage of SF_6 (72.4 kV). In some cases (Figure 7a, 0.20MPa and Figure 7b, 0.15MPa) the performance of SF_6 is approximately two–three times better than the c-C_4F_8 mixture. By comparing the breakdown voltages, it can be seen that 20%c-C_4F_8/80%N_2 has the potential to replace SF_6 in an extremely non-uniform electric field.

As an alternative to SF_6, many other aspects of c-C_4F_8 electrical properties are relevant, including the breakdown characteristics under a slightly non-uniform electric field, partial discharge characteristics, and toxicity of decomposition products. In [15], results showed that the AC breakdown voltage of c-C_4F_8 is 1.4 times that of SF_6 under a slightly non-uniform electric field. Results from the literature [17] also indicated that the partial discharge performance of 20%C_4F_8/80%N_2 is similar to that of 20%SF_6/80%N_2. The authors of [18] found that the product components of c-C_4F_8 are mainly fluorocarbon gas, such as CF_4, C_2F_6 C_2F_4 C_3F_8 and C_3F_6. From the above electrical properties, c-C_4F_8 has potential to replace SF_6 used in low- and medium-voltage equipment.

4. Conclusions

1. In an extremely non-uniform electric field, the breakdown voltages of 20%c-C_4F_8/80%N_2 increase with the increase in pressure, electrode distance, and the volume fraction of c-C_4F_8. As the pressure increases, a "hump" occurs owing to the homogenization of an electric field through the corona. With the increase in electrode distance, the AC breakdown voltages of c-C_4F_8/N_2 increase slightly in the case of a short gap, and increase significantly in the case of a long gap.
2. Based on a comparison between SF_6 and 20%SF_6/80%N_2, it was found that under the same conditions, the breakdown voltage of 20%c-C_4F_8/80%N_2 can reach up to 46–90% that of 20%SF_6/80%N_2. At 0.3 MPa, the breakdown voltage of 20%c-C_4F_8/80%N_2 can reach over 57% that of SF_6.
3. In an extremely non-uniform electric field, considering the insulation level and liquefaction temperature, a 20%c-C_4F_8/80%N_2 mixture has the potential to replace SF_6 in low- and medium-voltage equipment.

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