Research on the Insulation Performance of New Environmentally Friendly Insulation Gas Hexafluoropropylene and Carbon Dioxide Mixed Gas

DongWei Sun, Yongyan Zhou*, Tang Nian, and Li Li

Key Laboratory of Sulfur Hexafluoride of China Southern Power Grid Co., Ltd., Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, Guangdong 510080, China.

*Corresponding author e-mail: zhouyongyan@sgcc.com.cn

Abstract. Sulfur hexafluoride (SF₆) gas is widely used as a gas insulation medium in medium and high voltage arc extinguishing or insulated electrical equipment, but the gas is a serious greenhouse effect gas and poses a great threat to the environment. This paper introduces a new environmentally friendly insulating gas of hexafluoropropylene (1-C₃F₆) with the liquefaction temperature of -29.4 ℃ and the global warming potential (GWP) equivalent to CO₂, and especially investigates its saturation vapor pressure characteristics and insulation performance. Under different electrode structures and voltage characteristics, the insulation characteristics of the 1-C₃F₆/CO₂ gas mixture were studied by changing the electrode distance and the pressure of gas mixture.

Keywords: Sulfur hexafluoride (SF₆), hexafluoropropylene, insulation characteristic, electrode structure.

1. Introduction
Sulfur hexafluoride (SF₆) gas is chemically inert, non-toxic, non-flammable, non-explosive and thermodynamically stable. Under standard atmospheric pressure, the breakdown voltage in uniform electric field is nearly 3 times that of air, and the arc extinguishing capacity is about 100 times that of air. It has excellent insulation and arc extinguishing performance. Therefore, the gas is widely used in high voltage electrical equipment and electrical systems [1]. However, SF₆ is a gas with serious greenhouse effect [2], its global warming potential energy (GWP) is about 23900 times that of CO₂ [3], and its survival time in the atmosphere is about 3200 years [4]. As is known to all, SF₆ gas is mainly used in the power industry and its emissions are mainly from power equipment [5-7]. It is an inevitable trend for the development of power grid enterprises to reduce, restrict or even prohibit the use of SF₆ gas in electrical equipment. Therefore, seeking an environment-friendly and excellent insulation substitute gas applied in electrical equipment has become a hot topic in domestic and foreign research.

In order to obtain insulating substitute gases with insulation strength equivalent to or better than SF₆, lower liquefaction temperature and relatively lower GWP value, major domestic and foreign research institutions and companies mainly focus on the following two aspects. On the one hand, it is to study the SF₆ mixed gas. Under the condition of ensuring the insulation strength of the gas mixture, using
buffer gases such as air, N2 and CO2 to reduce the application of SF6 [8-11]. However, this method cannot completely eliminate the use of SF6 gas, and fundamentally cannot solve the greenhouse effect problem. After SF6 is mixed with other gases, its liquefaction temperature will be lowered, which can realize the application of SF6 mixed gas in alpine regions, which has certain significance in engineering [12-13]. Due to the addition of other gases in SF6, the insulation and arc extinguishing performance of the mixed gas are reduced, which limits its scope of application to a certain extent [14]. On the other hand, looking for a strong electronegative insulating substitute gas or its mixed gas to completely replace the application of SF6 in gas insulated equipment. At present, these substitute gases mainly include following aspects: (1) Conventional gases, such as air, N2 and CO2, etc. Replace SF6, completely restrict the application of SF6, and fundamentally reduce SF6 emissions [15-18]. Through further research, it is found that although this type of gas has a low liquefaction temperature, stable properties, and a low GWP value [19], its electronegativity is small, and its electron adsorption capacity is much less than that of SF6, and its insulation strength is less than 40% of SF6 [20]. At the same time, in terms of arc extinguishing performance, conventional gases such as air, N2 and CO2 are far from SF6 [21-23]. (2) PFC gases, such as CF4, C3F8, c-C4F8, etc., but the GWP value of these gases is still very high, and at the same time they are also affected by factors such as temperature and air pressure during use [24-25]; (3) CF3I Gas, the GWP value of CF3I gas is equivalent to CO2 gas, the life span in the atmosphere is only 1~2 d, and its insulation strength is better than that of SF6 gas, which has superior dielectric strength and GWP value. However, CF3I gas is easy to decompose during the application process, and the decomposition products have an impact on the arc extinguishing and insulation properties [26]; (4) Perfluoronitrile gas and all Fluorine ketone gas, such as C4F7N gas, C5F10O gas [27-28].

At present, C4F7N and C5F10O have become two gases that have attracted much attention. Based on DFT theory and ReaxFF molecular dynamics simulation, Zhang and others calculated the decomposition characteristics of C4F7N/CO2 mixture gas and the compatibility of C4F7N mixture gas with copper, aluminum, silver and other materials in the equipment [29-30]. The French Alston company reported an environmentally friendly insulating gas named g3 (C4F7N/CO2). The insulation performance of 3.7%-20% C4F7N/CO2 mixed gas was tested, and it was found that the insulating strength of the mixed gas with a mixing ratio of 20% was comparable to that of the mixed gas. SF6 is quite [31]. Simka and Stoller of ABB Company have studied the feasibility of C5F10O gas as an alternative gas for SF6. The results of the study show that under certain conditions, a mixture of C5F10O and CO2 or O2 can achieve insulation strength similar to that of SF6, but the arc extinguishing ability is relatively poor [32-33]. Based on the local thermodynamics and chemical equilibrium theory, Li and others established a chemical kinetic model for the decomposition of C5F10O gas, calculated the transition state and reaction rate of the decomposition of C5F10O, and the two main thermal decomposition products C4F7O and C3F4O [34]. Although the above two gases have developed corresponding medium and high voltage power equipment and carried out demonstration applications, heptafluoroisobutyronitrile has a certain carcinogenic risk and its own GWP value is still high. The liquefaction temperature of perfluoropentdanone is very high, and the application environment Limited, the insulation performance is difficult to meet the needs of high-voltage equipment.

This article introduces a new type of environmentally friendly insulating gas—hexafluoropropylene (1-C3F6). Its molecular structure is shown in Figure 1. Its liquefaction temperature is -29.4°C, and its global warming potential (GWP) is equivalent to CO2.
The liquefaction temperature and global warming potential of 1-C$_3$F$_6$ gas and some other gases that have been studied more are compared in Table 1 [35]. It can be seen from the table that the liquefaction temperature of 1-C$_3$F$_6$ in the following gaseous medium is lower, and the GWP value is much smaller than that of SF$_6$. The insulation characteristics of 1-C$_3$F$_6$ was first reported by Aschwanden and Biasiutti in 1981, the dielectric strength of 1-C$_3$F$_6$ gas was studied under the condition of inflation pressure of 0.07~2 bar. It was found that at 20°C and 0.87 bar, the critical breakdown field strength of 1-C$_3$F$_6$ is equivalent to that of SF$_6$[36], which can be used as a new environmentally friendly insulating gas for further research. In 2015, Wada et al. found that when the GWP of the mixed gas of 1-C$_3$F$_6$ is reduced to 0.26% of SF$_6$, the dielectric strength can still maintain 84% of SF$_6$[37]. 1-C$_3$F$_6$ has the potential to replace SF$_6$ in medium voltage equipment. Therefore, this article will continue to study the saturated vapor pressure characteristics of the 1-C$_3$F$_6$/CO$_2$ mixed gas and the insulation characteristics under the voltage characteristics of different electrode structures. By changing the gas pressure, the electrode distance and the ratio of the mixed gas, the influence of the gas on the insulating properties of 1-C$_3$F$_6$ is studied.

### Table 1. The liquefaction temperature and GWP of different gaseous medium

| gas medium | Liquefaction temperature/℃ | GWP       | Atmospheric lifetime |
|------------|----------------------------|-----------|----------------------|
| SF$_6$     | -63.8                      | 23,900    | 3200 a               |
| C$_3$F$_7$N| -4.7                       | 2,100     | 22 a                 |
| C$_2$F$_6$O| 26.5                       | 1         | 15 d                 |
| CF$_3$I    | -22.5                      | <5        | 2 d                  |
| c-C$_3$F$_6$| -8                        | 8,700     | 3220 a               |
| 1-C$_3$F$_6$| -29.4                     | 100       | 10 a                 |

2. Saturated vapor pressure characteristics of a new environmentally friendly gas mixture

2.1. Calculation method

This paper uses the method of combining the Antoine vapor pressure equation and the basic law of gas-liquid equilibrium to analyze and study the saturated vapor pressure characteristics of the 1-C$_3$F$_6$/CO$_2$ mixed gas to determine its applicable mixing ratio and pressure characteristics.

\[
\log P_1 = A_1 - B_1/(T + C_1) \quad (1)
\]

\[
\log P_2 = A_1 - B_1/(T + C_1) \quad (2)
\]

\[
P_{1x} = P_1 y \quad (3)
\]

\[
P_2(1-x) = P(1-y) \quad (4)
\]
$P_1$ and $P_2$ are the saturated vapor pressure of components 1 and 2, $P$ is the saturated vapor pressure of the mixed gas, $T$ is the liquefaction temperature of the mixed gas, and $A_1, B_1, C_1$ and $A_2, B_2, C_2$ are the components, respectively. The Antoine characteristic constants of 1 and 2, $x$ and $y$ are the molar ratios of the liquid and vapor phases of component 1 in vapor-liquid equilibrium.

Derived from equations (1) ~ (4):

\[
\frac{P_y}{10^{A_1-B_1/(T+C_1)}} + \frac{P(1-y)}{10^{A_2-B_2/(T+C_2)}} = 1
\]  

Due to the lack of Antoine characteristic constants of 1-C$_3$F$_6$ gas, the saturated vapor pressure data obtained from the experiment is used in the calculation, and it is obtained by fitting with the global optimization algorithm. Since the liquefaction temperature of the new environmentally friendly insulating gas 1-C$_3$F$_6$ is -29.4℃, it needs to be mixed with the buffer gas. Therefore, this project has calculated and analyzed the saturated vapor pressure characteristics of the mixed gas of 1-C$_3$F$_6$ gas and CO$_2$. Figure 2 shows the saturated vapor pressure characteristics of the mixed gas under different mixing ratios. As the temperature increases, the saturated vapor pressure of the mixed gas shows an upward trend. At 0℃, the saturated vapor pressure of the 1% 1-C$_3$F$_6$/CO$_2$ mixed gas reaches 1.39 MPa, which is much higher than the gas pressure commonly used in power equipment. As the ratio of 1-C$_3$F$_6$ increases and the temperature decreases, the saturated vapor pressure of the mixed gas decreases rapidly. When the minimum temperature limit is -25℃, the maximum allowable pressure for 5% 1-C$_3$F$_6$/CO$_2$ mixed gas is about 1.41 MPa, and the maximum allowable pressure for 20% 1-C$_3$F$_6$/CO$_2$ mixed gas is about 0.54 MPa; At -15℃, the maximum operating pressure of 5%, 15% and 20% 1-C$_3$F$_6$/CO$_2$ mixed gas is about 2.17 MPa, 1.02 MPa and 0.80 MPa respectively. These data can provide reference and basis for formula selection of insulation and arc extinguishing medium in environmentally friendly power equipment.

![Fig. 2 1-C$_3$F$_6$/CO$_2$ saturated vapor pressure in different proportions](image)

### 3. Analysis of Insulation Performance of New Environment-friendly Mixed Gas

#### 3.1. Test platform

The 1-C$_3$F$_6$/CO$_2$ mixed gas insulation test platform is composed of three parts: test prototype, voltage source and gas circuit system. The three different electrode structures of the test prototype are a flat electrode, an isolated fracture electrode and a needle plate electrode, which represent a uniform electric field, a slightly uneven electric field, and an extremely uneven electric field. This paper studies the variation of the insulation characteristics of the 1-C$_3$F$_6$/CO$_2$ mixed gas under different electrode structures and voltage characteristics. Before carrying out the electrical insulation test, the gas mixing device needs to be debugged and calibrated. Comparing the results of the test gas mixture with the results
of the National Standard Material Testing Center of the Chinese Metrology Institute, the maximum deviation is only 0.34%. For the study of other characteristics, it can be ignored, which provides a basis for the preparation of the test gas. Electrode size: (1) The diameter of the plate electrode is 50 mm, the thickness is 10 mm, and the edge is a spherical shape with a radius of 5 mm to ensure the uniformity of the electric field. The connecting shaft is a cylinder with a diameter of 20 mm and a length of 40 mm. (2) The ball-plate electrode adopts a cylindrical electrode with a diameter of 5 mm, a total length of 37.5 mm, and a spherical end with a radius of 6.3 mm; (3) The isolation fracture electrode adopts a high-voltage end electrode with a diameter of 115 mm and a ground electrode diameter of 52 mm; (4) The diameter of the needle electrode is 2 mm, the total length is 37.5 mm, and the end is spherical with a radius of 1 mm.

3.2. Experiment method
The impulse voltage generator is used to generate the impulse voltage to simulate the overvoltage caused by the lightning discharge, and the breakdown voltage value of 50% of the fracture gap is calculated by the buck-boost method, and the power frequency power supply is used to simulate the voltage characteristics under the power frequency condition. The DC power supply simulates the voltage characteristics under DC conditions. Among them, the lightning impulse insulation characteristic test is based on the up-and-down method specified in GB/T16927.1-2001 to obtain the 50% impulse breakdown voltage, that is: determine an initial voltage $U_1$ and each level voltage range $\Delta U$, $\Delta U$ according to each set of test conditions $= 0.01~0.06U_{50\%}$. During the test, if the isolating switch can withstand $U_1$, the applied voltage $U_2=U_1+\Delta U$, if it does not withstand $U_1$, then $U_2=U_1-\Delta U$. Carry out 50 tests according to this method, select $U_i$ that has appeared more than twice as valid data, and find the arithmetic average. When the AC breakdown test is in progress, slowly increase the voltage until the gap breakdown, record each breakdown voltage, repeat 50 times, and find the average value. The interval between each test is 5 min, so that the gas insulation is fully restored. When the DC breakdown test is in progress, the applied voltage starts from 0 kV and rises at a constant speed of 10 kV/min until the air gap is broken down. The discharge voltage is recorded as the DC breakdown voltage. The breakdown test is repeated 50 times at 5 min intervals to obtain the average breakdown voltage value. Take the average of 50 groups of valid data (the valid data in this article is defined as the relative square deviation of the breakdown voltage of 50 consecutive groups $<3\%$), and the time interval of the 2 groups of breakdown tests is 5 min to reduce the impact of the previous discharge. The measurement error is less than 1%, and the test cavity adopts a spiral micrometer to adjust the distance, and the distance adjustment accuracy can reach 0.01 mm.

4. Test results and comparative analysis
Since the positive and negative electrodes of the plate electrodes have the same and symmetrical structure, the values are equivalent under the positive and negative lightning impulse voltages. Therefore, unless otherwise specified in the text, only the test results under the negative lightning impulse voltage are used for comparative analysis.

4.1. The insulation characteristics of 1-C$_3$F$_6$/CO$_2$ under different electrode structures

4.1.1. The Insulation characteristics of 1-C$_3$F$_6$/CO$_2$ under uniform electric field. The 50% breakdown voltage of pure 1-C$_3$F$_6$ gas in the plate electrode changes with the electrode distance under 1 bar pressure. It can be seen from the figure that when the electrode distance is 5 mm, the 50% breakdown voltage is 31.64 kV; when the electrode distance is 10 mm, the electrode distance is 82.05 kV, and the voltage rise rate is 10.08 kV/mm. In the form of lightning impulse voltage, with the increase of the electrode distance, the 50% breakdown voltage increases approximately linearly. It can be seen that under a uniform electric field, the ability of 1-C$_3$F$_6$ gas to withstand lightning impact increases the fastest as the electrode distance increases. In the design of electrical equipment products, the insulation withstand strength of lightning impact can be improved by increasing the distance.
The fixed partial pressure of 1-C₃F₆/CO₂ mixed gas at 1-C₃F₆ gas is 1.25 bar (-25°C saturated vapor pressure), the electrode distance is 5 mm, and the 50% breakdown voltage of 1-C₃F₆/CO₂ mixed gas changes with electrode distance law. It can be seen from the figure that at 2 bar, the 50% breakdown voltage of the 1-C₃F₆/CO₂ mixture is 86 kV. At the same time, with the addition of buffer gas, there is a relatively obvious change in the improvement of gas insulation performance. It can be seen that the synergistic effect of 1-C₃F₆ and CO₂ in the 1-C₃F₆/CO₂ mixed gas is conducive to improving the overall insulation strength. In a uniform electric field, the power frequency insulation withstand strength can be enhanced by increasing the air pressure.

Figure 5 shows the change of the power frequency breakdown voltage of SF₆ and three potential substitute gases with the inflation pressure in the plate electrode with the electrode distance of 5 mm. Among them, SF₆ is pure gas. Fix the three gases 1-C₃F₆, C₄F₇N and C₅F₁₀O at -25°C when the saturated vapor pressure partial pressure is 1.25 bar, 1.0 bar and 0.38 bar, respectively, increase CO₂ and dry air, and study the change rule of power frequency breakdown voltage with charging pressure. It can be seen from the figure that the power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixed gas increases approximately linearly with the increase in the inflation pressure. At 1.25 bar, the power frequency breakdown voltage is 49.8 kV, which is almost at On the curve of SF₆, it can be seen that the power frequency breakdown voltage of SF₆ is equivalent to that of SF₆ under the charging pressure condition, which provides further development potential for the application of this gas in medium voltage power products. After 1-C₃F₆ is mixed with CO₂, the dielectric strength increases linearly with the increase of the pressure. When the pressure of the mixed gas rises to 7 bar, the power frequency breakdown voltage
is 132.7 kV, and the rate of rise is 14.4 kV/bar, which is similar to that of C₄F₇N/ The rising rate of CO₂ mixed gas (14.5 kV/bar) is close. Under various charging pressures, the power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixed gas is higher than that of the C₅F₁₀O/Air mixed gas. For example, at 3 bar, the power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixed gas is 66.6% of SF₆, but it is 1.2 times that of the C₅F₁₀O/Air mixed gas. The power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixed gas is significantly better than that of the C₅F₁₀O/Air mixed gas, which has the potential for application in medium voltage electrical equipment.

![Graph](image1)

**Fig. 5** Variation of power frequency breakdown voltage of several gases with pressure

4.1.2. The insulation characteristics of 1-C₃F₆/CO₂ under a slightly uneven electric field. When the electrode distance of the isolated fracture electrode is less than 20 mm, the electric field is close to a slightly uneven electric field, and the insulation characteristics of 1-C₃F₆/CO₂ are studied under this electric field. Under the isolation fracture, the electrode distance is 5 mm, and the fixed partial pressure of 1-C₃F₆ gas is 1.25 bar (-25 ℃ saturated vapor pressure). When the voltage form is power frequency voltage, when the CO₂ inflation pressure is gradually increased, power frequency breakdown the change rule of voltage is shown in Figure 6.

![Graph](image2)

**Fig. 6** Variation of power frequency breakdown voltage with pressure

Figure 6 shows the isolation fracture, the electrode distance is 5 mm, the fixed partial pressure of 1-C₃F₆ gas is 1.25 bar (-25°C saturated vapor pressure), when the voltage form is power frequency voltage, the CO₂ inflation pressure is gradually increased. The change rule of frequency breakdown voltage. It can be seen from the figure that at 1.25 bar, the power frequency breakdown voltage is 45.6 kV, when the air pressure rises to 5 bar, the power frequency breakdown voltage is 94.4 kV, and the rate of increase is 13.0 kV/bar. It can be seen that in a slightly uneven electric field, increasing the inflation pressure can
increase the lightning impulse insulation withstand strength. Similar to the uniform electric field, the insulation withstand strength increases approximately linearly.

4.1.3. The insulation characteristics of 1-C$_3$F$_6$/CO$_2$ under extremely uneven electric field. Figure 7 shows the fixed partial pressure of 1-C$_3$F$_6$/CO$_2$ mixed gas in 1-C$_3$F$_6$ gas under the spherical plate electrode is 1.25 bar (-25°C saturated vapor pressure), the electrode distance is 5 mm, and when the CO$_2$ charging pressure is gradually increased, the change rule of power frequency breakdown voltage. It can be seen from the figure that at 1.25 bar, the power frequency breakdown voltage is 45.3 kV, when the air pressure rises to 5 bar, the power frequency breakdown voltage is 98.7 kV, and the rate of increase is 14.0 kV/bar. It can be seen that under the extremely uneven electric field ball plate electrode, as the inflation pressure increases, the power frequency breakdown voltage of the 1-C$_3$F$_6$/CO$_2$ mixture increases linearly with the increase in the inflation pressure.

![Fig. 7 Variation of power frequency breakdown voltage of 1-C$_3$F$_6$/CO$_2$ mixed gas with pressure](image)

Figure 8 is under the needle plate electrode, the 1-C$_3$F$_6$/CO$_2$ mixed gas is at a fixed partial pressure of 1.25 bar (saturated vapor pressure at -25°C), and the CO$_2$ inflation pressure is gradually increased. When the voltage form is power frequency voltage, the electrode distance is 5 mm, the change rule of power frequency breakdown voltage. It can be seen from the figure that as the inflation pressure increases, the power frequency breakdown voltage of the 1-C$_3$F$_6$/CO$_2$ mixture gradually rises, but when the inflation pressure is 4 bar, the power frequency breakdown voltage is 46.6 kV and 5 bar. The power frequency breakdown voltage is 46.8 kV. In this charging pressure range, the power frequency breakdown voltage does not increase with the increase of the charging pressure. It shows that the insulation strength of the 1-C$_3$F$_6$/CO$_2$ mixed gas will be saturated when the pressure changes above 4 bar. In the range of 1.25 bar to 4 bar, the power frequency breakdown voltage basically increases linearly. At 1.25 bar, the power frequency breakdown voltage is 33.1 kV, and the rate of increase is 2.75 kV/bar. Under the extremely uneven electric field needle plate electrode, the growth rate of the power frequency breakdown voltage with the increase of the inflation pressure is also low, and the phenomenon of saturation gradually appears.
Fig. 8 Variation of power frequency breakdown voltage of 1-C₃F₆/CO₂ mixed gas with pressure

Figure 9 shows the mixed gas of 1-C₃F₆ and CO₂ in the needle plate electrode, the polarity is positive, the electrode distance is 5 mm, the partial pressure of 1-C₃F₆ is 1.25 bar, and the partial pressure of 1-C₃F₆ is fixed unchanged and increased. The CO₂ content, the DC breakdown voltage of the mixed gas and the change law of the charging pressure. It can be seen from the figure that at 1.25 bar, the DC breakdown voltage is 33.1 kV, when the air pressure rises to 5 bar, the DC breakdown voltage is 48 kV, and the rate of increase is 4.0 kV/bar. In the test, with the increase of the inflation pressure, the DC breakdown voltage showed an overall increasing trend, and the growth rate decreased slightly with the increase of the inflation pressure.

Fig. 9 Variation of DC breakdown voltage of 1-C₃F₆/CO₂ mixed gas with pressure

5. Conclusion

The saturated vapor pressure characteristics of the 1-C₃F₆/CO₂ mixed gas and the change of the insulation characteristics under different electrode structures and voltage characteristics are studied in this paper. The results show that the addition of CO₂ to the 1-C₃F₆ gas can reduce its liquefaction temperature and increase the saturation. The vapor pressure value, with the increase of the CO₂ gas mole fraction in the mixed gas, the relative insulation strength of the mixed gas of 1-C₃F₆ and CO₂ increases significantly. In a uniform electric field (plate electrode), when the 1-C₃F₆ gas partial pressure is 1.25 bar, the 1-C₃F₆ pure gas power frequency breakdown voltage is 49.8 kV, which is equivalent to the insulation level of SF₆. Under various charging pressures, the power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixed gas is higher than that of the C₅F₁₀O/Air mixed gas. With the increase of electrode distance and charging pressure, the insulation strength of the 1-C₃F₆/CO₂ mixed gas increases linearly.
Therefore, under the condition of uniform electric field, the withstand strength of shock and power frequency voltage can be enhanced by increasing the inflation pressure of the mixed gas. In medium voltage electrical equipment, the 1-C₃F₆/CO₂ mixed gas has the value of further product application research and can be used as an SF6 substitute gas for further research. In a slightly uneven field (isolated fracture electrode), the power frequency insulation strength of the 1-C₃F₆/CO₂ mixed gas increases linearly with the increase of the inflation pressure, and the rate of increase is faster. In an extremely uneven electric field, under the ball-plate electrode, as the inflation pressure increases, the power frequency breakdown voltage of the 1-C₃F₆/CO₂ mixture increases linearly with the increase of the inflation pressure; at the needle plate electrode Under the circumstances, the growth rate of the power frequency breakdown voltage with the increase of the inflation pressure is relatively low, and the phenomenon of saturation gradually appears.

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