Study on Partial Discharge Characteristics of $C_6F_{12}O$ Mixed Gas

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Abstract

The greenhouse effect of SF_6 increasingly limits its application in various gas insulated equipment. $\text{C}_6\text{F}_{12}\text{O}$ combines the advantages of insulation resistance, safety and environmental protection. When mixed with buffer gas, $\text{C}_6\text{F}_{12}\text{O}$ is considered to have potential application prospects in medium and low voltage equipment. In this paper, about the partial discharge characteristics of the mixed gas, an experimental study was carried out. The partial discharge initiation voltage and discharge extinction voltage of mixed gas under power frequency voltage are measured and compared with the breakdown voltage. The results show that with the increase of mixing ratio, the partial discharge initiation voltage and extinction voltage of mixed gas gradually increase, and the effect of gas pressure on high mixing ratio is obvious. The difference between the partial discharge inception voltage and the breakdown voltage is larger than that of pure N_2 . The research in this paper can provide an important reference for the application, operation and protection of $\text{C}_6\text{F}_{12}\text{O}$ mixed gas in medium and low voltage equipment.

1. Introduction

Gas insulated equipment is widely used in power systems due to its miniaturization and stable insulation performance. Its main insulating medium is SF_6 , which has a high Global Warming Potential (GWP). The GWP value of SF_6 is approximately 23500 times that of CO_2 ^[1], limiting its use is the current environmental demand. Using new environmental protection gas as insulation medium has become a hot spot in the current research of the global power industry.

$\text{C}_6\text{F}_{12}\text{O}$ of ketones fluoride is also a substance with excellent insulating properties. This substance is non-flammable, non-explosive and non-toxic. It has a boiling point of 49°C under standard conditions and a molecular weight of 316. It is used as a cover gas for fire extinguishing agents, magnesium treatment, and two-phase immersion cooling. The GWP value of the substance is 1, which has no destructive effect on the ozone layer, and the dielectric strength is 1.7 times higher than SF_6 ^[3]. The GIS electrical performance test of 145kV shows that adding $\text{C}_6\text{F}_{12}\text{O}$ to the air can achieve the same insulation strength as SF_6 ^[9]. The molecular formula of this substance is shown in Fig. 1.

J.D. Mantilla of ABB company in Switzerland found that when the mixture of $\text{C}_5\text{F}_{10}\text{O}$, $\text{C}_6\text{F}_{12}\text{O}$ and air was proportional to a certain proportion, the power frequency AC breakdown voltage of the mixture can reach three times that of air and carbon dioxide. Although these are not as high as the breakdown voltage of SF_6 under the same conditions, it can reach the level of SF_6 at a lower pressure by increasing the pressure of the mixture. At the same time, he also observed that the mixed gas obtained by adding a small amount of $\text{C}_6\text{F}_{12}\text{O}$ to the air has significantly improved the withstand voltage level of the air under the lightning impulse voltage ^[10]. Zhao Mingyue of Chinese Academy of Sciences studied the decomposition products of $\text{C}_6\text{F}_{12}\text{O}/\text{N}_2$ gas mixture and $\text{C}_6\text{F}_{12}\text{O}/\text{air}$ mixture after corona discharge, and concluded that $\text{C}_6\text{F}_{12}\text{O}/\text{N}_2$ mixture gas decomposes more products after corona discharge and may produce CF_3CN toxic

substances^[11]. It is found that the breakdown voltage of 3% C₆F₁₂O/N₂ mixture gas at atmospheric pressure is 1.7 times higher than that of pure N₂ breakdown voltage, which is equivalent to the breakdown voltage of 10% SF₆/N₂ mixture gas, and there is no decreasing trend of breakdown voltage after 100 times breakdown experiments. CF₄, C₂F₆, C₃F₆ and other fluorocarbons were obtained by analyzing the decomposition products of the mixture gas after breakdown^[12]. When the pressure is 0.10MPa-0.30MPa, the partial discharge inception voltage of 3% C₆F₁₂O/N₂ mixture was lower than that of 10% SF₆ gas mixture, while the partial discharge inception voltage of 3% C₆F₁₂O/N₂ mixture was lower than that of 10% SF₆ gas mixture. The liquefaction temperature of C₆F₁₂O is high, which needs to be mixed with buffer gas when used as insulating material. Therefore, it can be considered to mix the substance with a single conventional gas to improve the insulation characteristics of the conventional gas. Due to the stable chemical nature of N₂, we need to further study the insulating properties of C₆F₁₂O/N₂ gas mixture, and give full play to its greater application potential of the mixed gas in low-voltage equipment such as gas insulated switchgear and ring network cabinets.

Gas insulation equipment often has various kinds of insulation defects such as impurity residue and metal protrusions, which makes the local electric field become non-uniform and cause partial discharge^[14]. In this paper, the partial discharge of C₆F₁₂O mixed gas at power frequency is studied.

Simultaneously measure the breakdown voltage value of the mixed gas under different conditions, and compare with the partial discharge voltage to summarize the partial discharge characteristics of the mixed gas.

2. Experiment

2.1. Experimental platform

Figure 2 shows the circuit diagram of the power frequency AC experiment.

1—AC power supply 2—AC voltage regulator 3—No halo test transformer 4—Protection resistance 5—Capacitor divider 6—Voltage meter 7—Discharge chamber 8—No sense detection impedance 9—Coupling capacitor 10—Oscilloscope

This experiment uses a needle plate electrode to simulate metal protrusion defects in the device. The needle plate electrode is made of brass material, the tip of needle electrode is a sphere with a radius of 0.3mm, the radius of the plate electrode is 50mm and the thickness is 8mm. The gap distance between the needle tip and the upper surface of the plate electrode is set to be 15mm constant and fixed to the closed air chamber. The electrode is shown in Fig. 3.

2.2 Experimental process

The main measurement data of this experiment include partial discharge inception voltage, partial discharge extinction voltage^[14] and breakdown voltage. Partial discharge inception voltage (PDIV) refers

to the voltage value when the partial discharge phenomenon occurs when the voltage gradually increases. Partial discharge extinguishing voltage (PDEV) means that when partial discharge occurs, the voltage continues to rise and a severe partial discharge begins to appear, at this time, the voltage value is gradually reduced, when the discharge amount is less than a certain value, the partial discharge phenomenon has just disappeared, record the voltage value at this time PDEV. Figure 4 shows typical pd signals measured during the test.

3. Experimental Results And Analysis

3.1. PDIV

The case where the PDIV of the mixed gas changes with the pressure under different mixing ratios and the case where the PDIV of the mixed gas changes with the mixing ratio under different pressures are shown in Figs. 5 and 6, respectively.

It can be seen from the figure that the PDIV value of the gas increases with the increase of the pressure and the gas mixing ratio. The pure N_2 has a PDIV value of 5.9kV at 0.1MPa and 7.2kV at 0.2MPa, with an increase of 1.3kV. The PDIV value of the 2% mixed gas was 6.7kV at 0.1MPa and 10.1kV at 0.2MPa, with an increase of 3.4kV. The PDIV values of the mixture of 4% and 6% mixed gas increased by 4kV and 4.6kV respectively in this changing pressure. It can be concluded that the mixed gas of the high mixing ratio increases the PDIV value faster as the pressure changes.

The relationship between the starting voltage and the pressure is fitted by the formula

$$U_{PDIV} = AP + B \quad (1)$$

U_{PDIV} is the PDIV value, A is the slope reflecting the rate of change of PDIV value with pressure, and P is the pressure. The PDIV value of the mixed gas exhibits a positive correlation with the pressure. The larger the value of A , the more obvious the PDIV value of the mixed gas is affected by the pressure. The results calculated after fitting are: $A_{0\%}=12.14$; $A_{2\%}=32.43$; $A_{4\%}=40$; $A_{6\%}=46.86$. From this, it can be concluded that the higher the mixing ratio, the greater the influence of the pressure on the gas mixture.

In Fig. 6, when 2% $C_6F_{12}O$ is added, the PDIV value of the gas increases rapidly. After adding 4% $C_6F_{12}O$ gas, the gas PDIV value increases slowly. And the higher the pressure, the faster the PDIV value increases. It can be concluded that the PDIV value will increase faster after N_2 is added with $C_6F_{12}O$ under high pressure, but as the mixing ratio increases the speed becomes slower at a certain pressure.

Table 1 shows the ratio of the PDIV value at different pressures of each group of mixed gases to the PDIV value of N_2 , reflecting the increase in the partial discharge starting voltage of the mixed gas obtained after the addition of $C_6F_{12}O$. It can be seen from the table that as the pressure and the mixing ratio increase, the ratio of the PDIV value of each mixed gas to the PDIV value of N_2 is higher. At the same

mixing ratio, as the pressure increases, the ratio of the PDIV value of the mixed gas to the PDIV value of N_2 gradually increases. From Table 1, the ratio of 2% mixed gas to pure N_2 increases from 1.14 times at 0.1MPa to 1.40 times at 0.2MPa with the increase of pressure, at the same time, when the mixing ratio is 6%, the ratio of PDIV of the mixed gas to PDIV of pure N_2 increases from 1.20 times of 0.1MPa to 1.63 times of 0.2MPa. so the mixed gas of high mixed ratio increases the PDIV value more obviously with the increase of pressure, which consistent with the results of the previous linear. At the same pressure, as the mixed ratio increases, the ratio of the PDIV value of the mixed gas to the PDIV value of N_2 also gradually increases. When the pressure is 0.1MPa and the mixing ratio of the mixed gas increases from 2–6%, the ratio of the PDIV value of the mixed gas to the PDIV value of N_2 is from 1.14 to 1.20, an increase of 5.3%; and when the pressure is 0.2MPa, the data changes from 1.40 to 1.63, an increase of 16.4%. From this it can be concluded that the addition of $C_6F_{12}O$ to N_2 will result in a more significant increase in the PDIV value of the mixed gas at higher pressure.

In summary, when the pressure is higher than 0.16MPa and the mixing ratio is higher than 2%, the PDIV value of the mixed gas is increased by 50% or more compared to pure N_2 .

Table 1 PDIV Ratio of $C_6F_{12}O$ mixed gas to pure N_2

Pressure /MPa	Mixing ratio			
	0%	2%	4%	6%
0.2	1	1.40	1.53	1.63
0.18	1	1.40	1.54	1.64
0.16	1	1.32	1.38	1.55
0.14	1	1.32	1.35	1.48
0.12	1	1.25	1.28	1.31
0.1	1	1.14	1.19	1.20

3.2. PDEV

In this experiment, the measurement results of the partial discharge extinction voltage according to the experimental procedure are shown in Figs. 7 and 8. The figures show the change of PDEV value with pressure under different mixing ratios and the change of PDEV value with mixing ratio under different pressures.

In Figs. 7 and 8, Similar to the change of gas PDIV value, as the mixing ratio and pressure increase, the gas PDEV value gradually increases. For pure N_2 , its PDEV value is 5.8kV at 0.1MPa, and its PDEV value is 6.9kV at 0.2MPa, an increase of 1.1kV. For 2% $C_6F_{12}O$, its PDEV value is 6.2kV at 0.1MPa, and its PDEV value is 9.2kV at 0.2MPa, an increase of 3kV. When the mixing ratio is 4%, the PDEV value of the mixed

gas at 0.1MPa is 6.4kV, which is not significantly improved compared to the 2% mixed gas. When it reaches 0.2MPa, it increases to 10.3kV and increases by 3.9kV. When the mixing ratio reaches 6%, the PDEV value of the mixed gas is 7kV at 0.1MPa, which is a relatively large increase compared to the ratio of 2% and 4%. At 0.2MPa, the PDEV value of the mixed gas is 10.6kV, which increases 3.6kV. Therefore, the addition of $C_6F_{12}O$ increases the PDEV value of N_2 , while the sensitivity to pressure increases slightly.

According to the formula (2), linearly fit each curve in Fig. 7 to study the linear relationship between the PDEV value of various mixed gases and the pressure.

$$U_{PDEV} = A'P + B' \quad (2)$$

Where U_{PDEV} is the partial discharge quenching discharge voltage value, and A' is the slope. The values of A' calculated for each curve are: $A'_{0\%}=11$, $A'_{2\%}=30.71$, $A'_{4\%}=36.71$, $A'_{6\%}=37.71$. The values of the four curves A' are all positive values, that is, the PDEV voltage value of each group of gases is positively correlated with the pressure. After adding $C_6F_{12}O$, the influence of pressure on the PDEV value of the mixed gas increases sharply, and the higher the mixing ratio of the mixed gas, the greater the PDEV value is affected by the pressure. The PDEV value of the mixed gas with a mixing ratio of 4% and 6% is approximately the same under the influence of pressure.

From Fig. 8, adding 2% $C_6F_{12}O$ will increase the PDEV value of N_2 , and as the pressure is increased, the magnitude of the increase also increases accordingly. However, the PDEV value of the mixed gas with a mixing ratio of 4% relative to the mixed gas of 2% has not increased much. At 0.14MPa and 0.18MPa, the PDEV values of the two mixed gases are almost equal. That is, as the mixing ratio continues to increase, the increasing trend of the PDEV value of the mixed gas gradually slows down.

Table 2 lists the ratio of the PDEV value of each group of mixed gas to the PDEV value of pure N_2 , further showing the partial discharge extinction voltage characteristics of the mixed gas. In the case where the mixing ratio is constant, the ratio of the PDEV value of the mixed gas to the PDEV value of N_2 gradually increases as the pressure increases. When the mixing ratio is 2% and the pressure is from 0.1 MPa to 0.2 MPa, the ratio of the PDEV value of the mixed gas to the PDEV value of N_2 increases from 1.07 to 1.33; At a mixing ratio of 6%, this value increased from 1.21 to 1.54. So the higher the mixing ratio, the higher the ratio of the PDEV value of the mixed gas to the PDEV value of N_2 . At a fixed pressure, the increase of the mixing ratio for the increase of the N_2 's PDEV value is as follows. At 0.1MPa, the ratio of the PDEV value of the mixed gas to the PDEV value of N_2 changes from 1.07 to 1.21 as the mixing ratio increases. At 0.2MPa, the ratio of the PDEV value of the mixed gas to the PDEV value of N_2 increases from 1.33 to 1.54 as the mixing ratio increases. It can be concluded that the higher the pressure, the higher the ratio of the PDEV value of the mixed gas to the PDEV value of pure N_2 , and the greater the increase in the PDEV value of the mixed gas relative to the pure N_2 . The PDEV value of 6% of the mixed gas at 0.18MPa and above can reach more than 1.5 times of N_2 under the same conditions.

Table 2 PDEV Ratio of C₆F₁₂O mixed gas to pure N₂

Pressure /MPa	Mixing ratio	0%	2%	4%	6%
0.2	1	1.33	1.49	1.54	
0.18	1	1.31	1.37	1.55	
0.16	1	1.27	1.35	1.46	
0.14	1	1.21	1.24	1.39	
0.12	1	1.12	1.22	1.29	
0.1	1	1.07	1.10	1.21	

3.3. Comparison of partial discharge voltage and breakdown voltage of mixed gas

This section compares the partial discharge characteristics and breakdown characteristics of the gas. Table 3 and Table 4 respectively list the ratio of partial discharge inception voltage and partial discharge extinction voltage to breakdown voltage of the mixed gas under different mixing ratios and different pressure conditions.

Table 3 PDIV value / breakdown voltage value

Pressure /MPa	Mixing ratio	0%	2%	4%	6%
0.2		0.62	0.37	0.34	0.36
0.18		0.58	0.37	0.34	0.35
0.16		0.57	0.38	0.32	0.34
0.14		0.58	0.40	0.33	0.35
0.12		0.61	0.41	0.34	0.34
0.1		0.69	0.40	0.35	0.34
average value		0.61	0.39	0.34	0.35

Table 3 shows that the ratio of the pure N₂'s PDIV value to the breakdown voltage value is concentrated around 0.6 at 0.1MPa-0.2MPa, when the mixing ratio is 2%, the ratio of the mixed gas's PDIV value to the breakdown voltage is about 0.4 at 0.1MPa-0.2MPa, so the partial discharge voltage of the mixed gas is

already smaller than the breakdown voltage value under the same conditions. When the mixing ratio is 4% and 6%, the ratio of the mixed gas's PDIV value to the breakdown voltage value is about 0.34 at 0.1MPa-0.2MPa. It shows that under this mixing ratio condition, the partial discharge starting voltage is great smaller than the breakdown voltage. It can be concluded that when the pure N₂ is partially discharged, the voltage value may be relatively close to the breakdown value. After adding C₆F₁₂O, the difference between the partial discharge voltage and the breakdown voltage of the gas increases significantly.

Table 4 PDEV value / breakdown voltage value

Pressure /MPa	Mixing ratio	0%	2%	4%	6%
0.2		0.59	0.34	0.32	0.32
0.18		0.57	0.33	0.30	0.33
0.16		0.55	0.35	0.31	0.31
0.14		0.57	0.36	0.30	0.33
0.12		0.58	0.35	0.31	0.32
0.1		0.67	0.37	0.32	0.33
average value		0.59	0.35	0.31	0.32

It can be seen from Table 4 that the ratio of the pure N₂'s PDEV value to the corresponding breakdown voltage value is 0.59 at 0.1MPa-0.2MPa, which is relatively close to the above-mentioned PDIV value. When the mixing ratio is 2%, the ratio of the mixed gas's PDEV value to the breakdown voltage value under the corresponding conditions is about 0.35 at 0.1MPa-0.2MPa. When the mixing ratio is 4% and 6%, this value is 0.31 and 0.32 respectively. The addition of C₆F₁₂O mixed gas can reduce the ratio of the pure N₂'s partial discharge extinction voltage to the breakdown voltage under corresponding conditions.

4. Application Analysis Of Cfo Mixed Gas Insulation Equipment

The smaller the partial discharge of the insulating equipment, the better the performance. The current standard stipulates that the level of partial discharge is mainly considering the usage time under the current common process conditions and under normal operating conditions. Through the experimental data analysis of the partial discharge characteristics of the C₆F₁₂O mixed gas in this paper, the results show that the discharge amount of the C₆F₁₂O mixed gas is small. However, the long-term partial discharge will cause destructive effects on the insulating material, and eventually lead to insulation equipment failure. Therefore, for new equipment, the discharge capacity should not exceed the specified value. When the discharge amount exceeds 1 times of the standard, although the impact on the

equipment is very small, it cannot be ignored. When the discharge amount exceeds 1–4 times of the standard, it is necessary to analyze the possible causes and monitor the operation. If it exceeds 10 times the standard value or even greater, it means that there may be serious hidden faults in the insulation equipment. Faults are usually exposed between 2 months and 2 years, and various invisible faults are often unable to be detected by other insulation tests. Therefore, the measurement of the $C_6F_{12}O$ mixed gas partial discharge experimental data can provide technical reference for the prevention of electrical equipment failures, and can also ensure the safe operation of the equipment, which has certain engineering reference significance.

5. Conclusion

- (1) The partial discharge inception voltage and partial discharge extinction voltage of the $C_6F_{12}O$ mixed gas gradually increases with the increase of the mixed gas and the mixing ratio. The partial discharge characteristic of mixed gas grows slowly with the increase of mixing ratio, and the pressure has a greater influence on the gas with a higher mixing ratio.
- (2) The breakdown voltage of pure N_2 is greatly improved after adding $C_6F_{12}O$, when the mixing ratio is 4% at a pressure of 0.18MPa or the mixing ratio is 6% at a pressure of 0.16MPa, the breakdown voltage can be achieved 2.5 times or more than the pure N_2 .
- (3) When comparing the partial discharge voltage with the breakdown voltage value, it was found that the partial discharge voltage value and the breakdown voltage value of the mixed gas after the addition of $C_6F_{12}O$ were smaller than that of pure N_2 .
- (4) The partial discharge of the $C_6F_{12}O$ mixed gas phase is small, which can provide technical reference for the safe operation of the $C_6F_{12}O$ mixed gas equipment and the prevention of electrical equipment failures, it has engineering significance.

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Figures

Figure 1

Molecular formula of C₆F₁₂O

Figure 2

Experimental circuit diagram

Figure 3

Size of the needle-plate electrode

Figure 4

Typical partial discharge waveform

Figure 5

PDIV with the pressure

Figure 6

PDIV with the mixing ratio

Figure 7

PDEV with the pressure

Figure 8

PDEV with the mixing ratio