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Decomposition Characteristics of SF_6/N_2 Under Partial Discharge of Different Degrees

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ABSTRACT SF_6/N_2 gas mixture can not only reduce the consumption of SF_6 in power system, but also effectively alleviate SF_6 greenhouse effect. Since SF_6/N_2 can decompose under the alternating current partial discharge(PD), its decomposition characteristics are closely related to PD attributes. Therefore, the fault diagnosis method can be established through its PD decomposition characteristics. However, at present, the decomposition characteristics of SF_6/N_2 mixed gas under PD have not been fully grasped, and the correlation characteristics between decomposition characteristics and PD intensity have not been obtained. To this end, this article uses pin-plate electrodes to simulate the typical metal protrusion insulation defects in GIS equipment. SF_6/N_2 decomposition experiments are conducted at different PD intensity to study the correlation between the PD decomposition characteristics of SF_6/N_2 mixed gas and PD intensity. The results show that: the generation rate of characteristic decomposition components such as SOF_2, SO_2, SO_2F_2, SOF_4, CF_4, CO_2, NO, NO_2, and NF_3 are positively correlated with PD intensity; NO_2 and (SO_2F_2+SOF_2+SOF_4+SO_2) can be used as the characteristic quantity to judge the whole process of PD, SO_2F_2 can be used as the feature to judge the early PD, and SOF_2 and SOF_4 can be used as the features to judge the severe PD. The results of this article will lay the foundation for the monitoring of equipment insulation status using SF_6/N_2 decomposition characteristics in the future.

INDEX TERMS Decomposition characteristics, partial discharge, PD quantity, SF_6/N_2.

I. INTRODUCTION

As the insulating gas of Gas Insulated Switchgear(GIS), SF_6/N_2 gas mixture can not only reduce the consumption of SF_6 in power system, but also effectively alleviate SF_6 greenhouse effect and solve the problem of high liquefaction temperature [1]–[4]. At present, State Grid Corporation has adopted 30% SF_6 and 70% N_2 gas mixture to apply in the GIS demonstration project [5]–[8]. Similar to conventional GIS, GIS using SF_6/N_2 gas mixture will inevitably be damaged during manufacturing, transportation, installation and operation, resulting in some internal insulation defects.. These insulation defects will deteriorate gradually in the long-term operation of GIS, and when they reach a certain degree, they will induce partial discharge (PD) in the equipment [9]–[15].

When PD occurs in GIS, SF_6 and N_2 in GIS will decompose under the action of discharge, and the decomposition products will react with the trace H_2O or O_2 mixed in the GIS to form SO_2F_2, SOF_2, NF_3, NO_2, H_2S, SOF_4, and other products [16], [17]. The types, contents and generative rule of these decomposition products are closely related to the types of insulation defects and the degree of PD. Therefore, PD caused by GIS internal defects can be judged through detection of decomposition components, so as to make early prediction and diagnosis of insulation defects, laying a foundation for GIS state assessment and fault diagnosis, and ensuring the safe and reliable operation of GIS equipment [18]–[25].

At present, domestic and foreign scholars have carried out some studies on the discharge decomposition of SF_6/N_2 mixed gas and obtained preliminary research results, but mainly focused on the experimental research on the characteristics of arc decomposition. For example, Gerusimov and Sidorkina conducted relevant experiments on the decomposition of SF_6/N_2 mixed gas under arc, and the discharge energy was 500W. At the same time, the main decomposition products of SF_6 under arc discharge were detected by infrared absorption spectroscopy, mainly including SOF_4 and SO_2F_2 [26]. AM Casanovas *et al.* found that the by-products produced by SF_6/N_2 gas mixture include SF_2, S_2F_2, SF_4,

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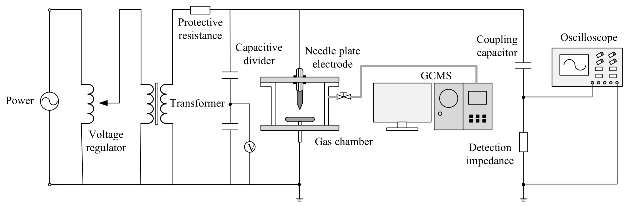

FIGURE 1. Wiring diagram of PD experiment platform.

HF, S_2F_{10}, SOF_2, SO_2F_2, SOF_4 and SO_2 generated by pure SF_6 under discharge condition, N_2O generated by pure N_2 under discharge condition. SF_6/N_2 mixture also produces new by-products NF_3 and N_2F_2 [16], [17].

However, at present, the decomposition characteristics of SF_6/N_2 gas mixture under PD have not been fully mastered, and the correlation characteristics between the types, contents and generation rules of SF_6/N_2 gas mixture discharge decomposition components and PD intensity have not been acquired. There is also no method for fault diagnosis and state assessment using the fault decomposition characteristics of SF_6/N_2 gas mixture. Therefore, this article focuses on the correlation characteristics between SF_6/N_2 gas mixture fault decomposition and PD strength, using a needle - plate electrode to simulate the insulation defects of metal outburst often found in GIS equipment. The SF_6/N_2 gas mixture PD decomposition experiment was conducted to study the correlation between SF_6/N_2 gas mixture PD decomposition and PD intensity.

II. TEST INTRODUCTION

A. TEST APPARATUS

To ensure a comprehensive analysis of decomposition characteristics of SF_6/N_2 gas mixture under PD, a SF_6/N_2 gas mixture PD test platform was built. The wiring diagram of the test platform is shown in Figure 1.

PD test platform is mainly composed of power supply, SF_6/N_2 gas chamber and detection system. The power supply is regulated by the voltage regulator (0∼380V), and the required voltage is provided by the high-voltage non-corona test transformer (10kVA/100kV). The voltage signal at the output end of the test transformer can be measured by the capacitive voltage divider. The protection resistor (10kΩ) can block the discharge current and reduce the noise interference from the power supply; The coupling capacitance provides a low impedance channel. When the voltage at both ends changes due to PD, it is coupled to the detection impedance through the coupling capacitor, and the PD signal is detected by the pulse voltage on the detection impedance. The SF_6/N_2 gas chamber made of stainless steel is well sealed. There are air inlet, air outlet, sampling port, observation window and pressure gauge on it. The detection system includes PD signal detection system and SF_6/N_2 characteristic decomposition component detection system. PD signals are detected by the pulse current parallel method recommended by IEC60270 and collected and stored by the Tektronix DPO7254C digital oscilloscope. The SF_6/N_2 decomposition characteristic component detection system adopts Shimadzu QP-2010Ultra Gas Chromatography-Mass Spectrometer (GC/MS) for quantitative detection. GC/MS uses gas chromatography column to separate the components of the mixed sample, and then uses mass spectrometry to carry out quantitative detection of each component after separation, which can not only complete accurate quantitative detection, but also separate the mixture.

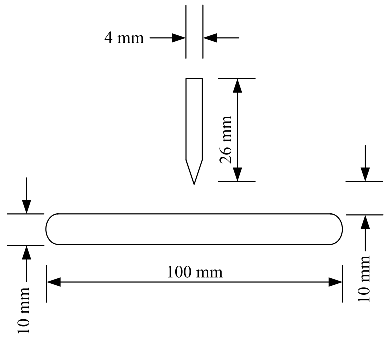

FIGURE 2. Insulation defect model of metal protrusions.

B. PHYSICAL MODEL OF INSULATION DEFECT

In this article, metal protrusion defects in GIS were simulated by a needle-plate electrode, as shown in Figure 2. The needle electrode and the plate electrode made of copper were polished. The radius of curvature and the angle of the cone tip of the needle electrode were 0.3 mm and 30°, and the diameter and thickness of the plate electrode were 100 mm and 10 mm. The distance between the needle electrode and the plate electrode was set to keep it at 10 mm.

C. TEST STEPS

In this article, 30%SF_6/70%N_2 gas mixture was used for the test. A large number of tests were carried out on the SF_6/N_2 PD decomposition test platform built above. All the tests were carried out at room temperature of 20°. The specific steps are as follows:.

1) Before the test, the inner wall and insulation defects of the gas chamber are cleaned with anhydrous ethanol to remove the residual dust and impurities, so as to avoid the influence of these impurities and dust and residual decomposition products that may adhere to the inner wall in the previous test. After that, the needle-plate defect model is put into the gas chamber.

2) The gas chamber is pumped to vacuum and maintained for 12h. Then SF_6/N_2 gas mixture is filled into the gas chamber. This process is repeated three times to remove impurities from the chamber.

3) After cleaning, SF_6/N_2 gas mixture is filled into the gas chamber until the pressure is 0.3MPa (absolute value). After stabilizing for 24 hours, a mirror dew point instrument is used to detect the H_2O content in the gas chamber, ensuring that the H_2O content is less than 500×10^{-6} (volume fraction), which is consistent with the requirements of industry standard DL/T596-2005 [27].

4) Voltage is boosted slowly to the needle-plate defect model, and PD initial voltage and breakdown voltage of the

defect model are obtained. Five different applied voltages are selected between the PD initial voltage and the breakdown voltage, and the PD intensity is adjusted by controlling the applied voltage. The PD initial voltage in this article is 25kV, and the breakdown voltage is 43kV. Therefore, five external application voltages of 28kV, 31kV, 34kV, 37kV and 40kV are selected for the test. Under the above five external application voltages, the average discharge per time is respectively 18pC, 35pC, 46pC, 73pC and 97pC.

5) The 96-hour PD decomposition test is conducted under each applied voltage. Before the test, gas mixture is collected from the gas chamber after standing for 24 hours to detect the content of each impurity. During the test, Tedlar PVF sampling bag is used to collect gas mixture every 12 hours, and then GC/MS is used to quantitatively detect each decomposition component.

III. DECOMPOSITION CHARACTERISTICS OF SF_6/N_2 MIXED GAS UNDER PD

A. SELECTION OF DECOMPOSITION PRODUCTS

The decomposition products of SF_6/N_2 gas mixture under PD contains all decomposition products of pure SF_6 gas under discharge condition. N_2, which is not easy to break the chemical bond, will also participate in a series of physical and chemical reactions under the continuous PD action. The reaction process involving N atoms may be as follows:

$$N_2 + O_2 \rightarrow 2NO \tag{1}$$

$$2NO + O_2 \rightarrow 2NO_2 \tag{2}$$

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO \tag{3}$$

$$N + 3F \rightarrow NF_3 \tag{4}$$

$$N + 3H \rightarrow NH_3 \tag{5}$$

$$4NH_3 + 6F \rightarrow NF_3 + 3NH_4F \tag{6}$$

$$3NF_3 + 5H_2O \rightarrow 2NO + HNO_3 + 9HF \tag{7}$$

$$4HNO_3 \rightarrow 4NO_2 + O_2 + 2H_2O \tag{8}$$

Through preliminary experiments, it is found that the key gas components produced by the decomposition of SF_6/N_2 gas mixture under PD mainly include: CO_2, NO, NO_2, NF_3, SO_2F_2, SO_2, SOF_2, CF_4 and SOF_4. HF is highly acidic and easily reacts with the internal electrodes and insulating materials of the test equipment. Therefore, it is not suitable as a characteristic decomposition product. NO is chemically very active and easily reacts with O_2. If the trace O_2 in the gas chamber is fully reacted and no longer remains, then it can be considered that NO can exist stably. For this reason, this article selects SOF_2, SO_2, SO_2F_2, SOF_4, CF_4, CO_2, NO, NO_2, NF_3 as the characteristic decomposition components of SF_6/N_2 gas mixture under PD for quantitative analysis.

B. DECOMPOSITION CHARACTERISTICS UNDER DIFFERENT PD QUANTITY

1) THE CHANGE CHARACTERISTICS OF THE CONTENT OF NITROGEN PRODUCTS WITH TIME

N_2 is a gas with very stable chemical properties. In general, it is not easy to break chemical bonds. However, under the action of high-energy electrons continuously excited by PD, the N≡N bond in N_2 can break gradually, and then N atoms can react with trace O_2 and free F generated by decomposition of SF_6 in the gas chamber to produce decomposition products such as NO_2 and NF_3.

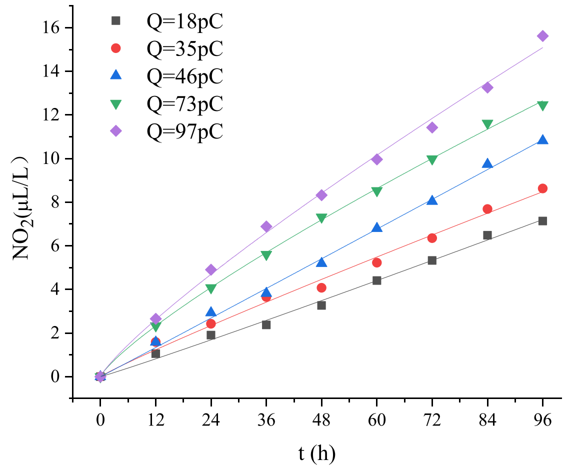

FIGURE 3. Change curve of NO_2 content with time.

(a) The change characteristics of NO_2 content with time

NO_2 is produced by the combination of O atoms and N atoms which are formed by N_2 decomposition under PD. The change curve of its content with time is shown in Figure. 3. As can be seen from the figure, with the increase of discharge time, the content of NO_2 increases steadily, and there is no obvious saturation trend during the test time.

This is because there is enough O_2 in the gas chamber in the early stage of discharge, so the content of NO_2 can increase steadily, but the overall content of NO_2 is not high, so the amount of O atoms needed to produce NO_2 is not high.

When the discharge quantity gradually increases, the NO_2 content also increases, but the increase rate does not change much. The slope of the NO_2 content change curve under different discharge quantity is relatively close.

This may be because N_2 is relatively stable and very few N atoms are generated in the discharge chamber when the discharge quantity increased, so the production of NO_2 is generally low.

(b) The change characteristics of NO content with time

Figure. 4 shows the change curve of NO content with time. With the increase of discharge time, the content of NO increases. There is a tendency towards saturation. In the early stage of discharge, the increase of NO content is relatively fast, but in the late stage, the growth rate of NO begins to slow down.

This is because O_2 in the gas chamber is sufficient in the early stage, and the content of NO increases relatively fast. With the consumption of O_2, the production rate of NO begins to slow down, while the chemically active NO reacts with O_2 to produce NO_2, so the growth rate of NO will slow down in the later stage of discharge. Moreover, very few N atoms are generated in the electrical chamber, so the overall content of NO is relatively low.

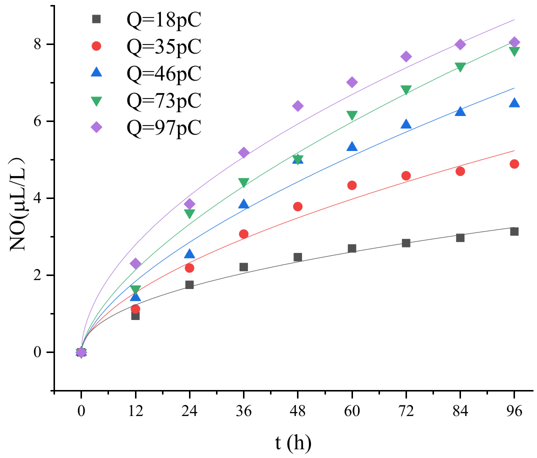

FIGURE 4. Change curve of NO content with time.

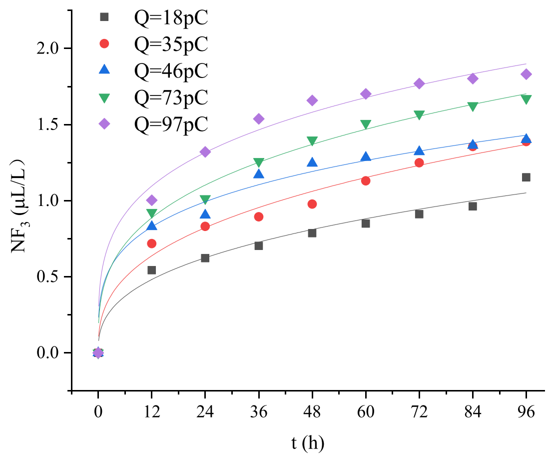

FIGURE 5. Change curve of NF_3 content with time.

By comparison, it can be found that the content of NO_2 generated under the same conditions is always higher than the content of NO. Through the analysis of equations (1) and (2), it can be found that when the ratio of active N_2 and O_2 in the reaction is 1:1, all NO will be generated. When the ratio of active N_2 to O_2 in the reaction is 1:2, all NO_2 will be generated. When the ratio of active N_2 and O_2 in the reaction is 1:1.5, equal amounts of NO and NO_2 will be generated. It can be inferred that the ratio of N_2 and O_2 in the reaction is between 1:1.5 and 1:2.

(c) The change characteristics of NF_3 content with time

NF_3 is also one of the products of SF_6/N_2 gas mixture under PD, and the change curve of its content with time is shown in Figure. 5. It can be seen that with the increase of discharge, the NF_3 content does not increase greatly.

This may be because there are few N atoms and F atoms in the gas chamber, and some N atoms combine with O atoms to generate NO_2 and NO. Therefore, with the increase of discharge, the content of NF_3 does not increase much. When the discharge quantity increased, more N atoms are generated in the discharge chamber, and the production of NF_3 is also increased. However, the increase of NO_2 and NO content also consumes more N atoms, so the increase of NF_3 is limited, and the overall content is still low.

2) THE CHANGE CHARACTERISTICS OF THE CONTENT OF SULFUR PRODUCTS WITH TIME

(a) The change characteristics of SO_2F_2 content with time

The change curve of SO_2F_2 content with time is shown in Figure. 6. It can be seen that, with the increase of time, the content of SO_2F_2 increases significantly under different discharge quantities. However, when the discharge quantity is low, the slope of the curve of SO_2F_2 content changing with time is relatively close. When the discharge quantity of PD rises above 73pC, both the production rate and the content of SO_2F_2 increase significantly. It can be seen that the production process of SO_2F_2 is closely related to the PD intensity.

SO_2F_2 is one of the main sulfur-containing products of SF_6 under PD. Because SF_6 loses F atoms under the action of discharge, the chemical properties of the low-sulfur fluoride molecular group are very active. At the same time, under the action of the high-energy electric field, the electrons collide with the small amount of O_2 molecules and H_2O molecules in the gas chamber to produce OH and O atomic groups. low-fluorine sulfide is very easy to interact with the O atoms and OH atomic groups in the gas chamber. They react to produce SO_2F_2, SOF_2, SOF_4 and so on. When the discharge intensity is relatively low, the decomposition generates less low-fluoride sulfide, so the content and growth rate of SO_2F_2 are relatively low. When the PD intensity increases, more electrons are excited, and the electrons collide strongly with SF_6, which promotes the formation of a large amount of low fluoride sulfur. These make the content and growth rate of SO_2F_2 increase. And there is no obvious saturation trend during the test time.

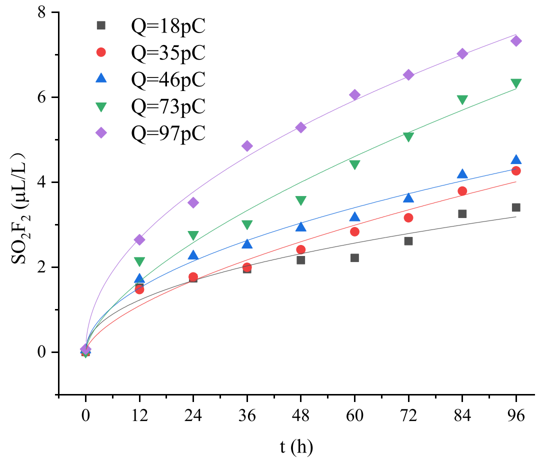

FIGURE 6. Change curve of SO_2F_2 content with time.

(b) The change characteristics of SOF_2 content with time

SOF_2, like SO_2F_2, is also one of the main sulfur decomposition products of SF_6 under PD. The change curve of its content with time is shown in Figure. 7. The change curve of SOF_2 content with time is similar to that of SO_2F_2. With the increase of discharge quantity, the content of SOF_2 increases significantly. When the PD strength is weak, SOF_2 content is

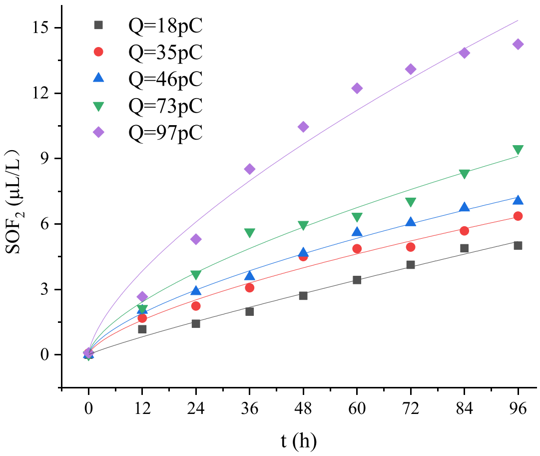

FIGURE 7. Change curve of SOF_2 content with time.

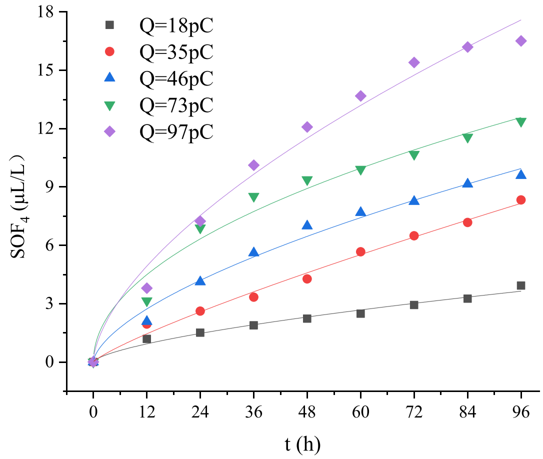

FIGURE 8. Change curve of SOF_4 content with time.

low, and the growth rate is relatively flat. However, when the discharge quantity increased to 97pC, SOF_2 content increases significantly, and the slope of the curve has a relatively large change.

Compared with SO_2F_2, SOF_2 content is always higher than SO_2F_2 at the same condition. Because SOF_2 and SO_2F_2 are produced by the reaction of low-sulfur fluoride with O atoms and OH atomic groups in the gas chamber. As the discharge intensity continues to increase, low-sulfur fluoride SF_5, SF_4, SF_2, and O atoms, OH groups will continue to increase. SF_6 is most easily decomposed into SF_5, which reacts with O and OH to generate SOF_2 and further hydrolyzes to generate SO_2F_2. However, the structure of SF_5 is not stable. In contrast, SF_4 and SF_2 are more stable because they have symmetrical structure. SF_4 can react with H_2O to produce SOF_2, and SF_2 can react with O to produce SOF_2. Therefore, the production of SOF_2 will be higher than that of SO_2F_2 under the same applied voltage or PD intensity. The relevant reaction process is as follows [21]:

$$SF_5+O_2 \rightarrow SO_2F_2+3F \tag{9}$$

$$SF_4+H_2O \rightarrow SOF_2 + 2HF \tag{10}$$

$$SF_4+O \rightarrow SOF_2+2F \tag{11}$$

$$SF_2+O \rightarrow SOF_2 \tag{12}$$

(c) The change characteristics of SOF_4 content with time

The change curve of SOF_4 content with time is shown in Figure. 8. When the discharge quantity is low, the change of SOF_4 content with discharge time is not obvious, and the content is also low. When the discharge quantity increased, the content of SOF_4 increases greatly with the increase of discharge time. Especially when the discharge quantity increased to 97pC, the SOF_4 content increases at a faster rate and the slope of the curve is relatively large.

SOF_4 is not stable in nature, and it is easy to hydrolyze with H_2O. Therefore, when the PD intensity is relatively low, on the one hand, there is less low fluoride generated by the decomposition of SF_6, on the other hand, the H_2O in the closed gas chamber is sufficient, so the content of SOF_4 relatively low. And the rate of increase is not large.

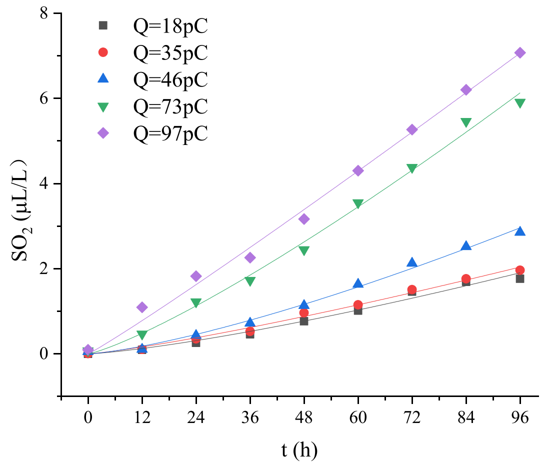

FIGURE 9. Change curve of SO_2 content with time.

With the increase of PD intensity, the content of low-fluoride generated by SF_6 decomposition will also increase, so more SOF_4 will be generated. In addition, when PD intensity is relatively high, the content of other products will also increase, and the generation of other products will consume H_2O in the gas chamber, reducing the hydrolysis reaction of SOF_4. Therefore, when the PD intensity is high, the content of SOF_4 increases greatly, and the increase rate is also relatively high. The relevant reaction process is as follows [21]:

$$SF_5+O \rightarrow SOF_4+F \tag{13}$$

$$SF_5+OH \rightarrow SOF_4+HF \tag{14}$$

$$SOF_4+H_2O \rightarrow SO_2F_2 + 2HF \tag{15}$$

(d) The change characteristics of SO_2 content with time

The change curve of SO_2 content with time is shown in Figure. 9. When the discharge quantity is relatively low, the three curves of SO_2 content over time are relatively close, and the content is also relatively low. With the increase of discharge quantity, the content of SO_2 increases obviously.

SO_2 is mainly produced by the hydrolysis of SOF_2, so the amount of SO_2 produced depends on the SOF_2 and H_2O. When the discharge quantity is low, H_2O in the gas chamber is relatively sufficient, but SOF_2 content is not high,

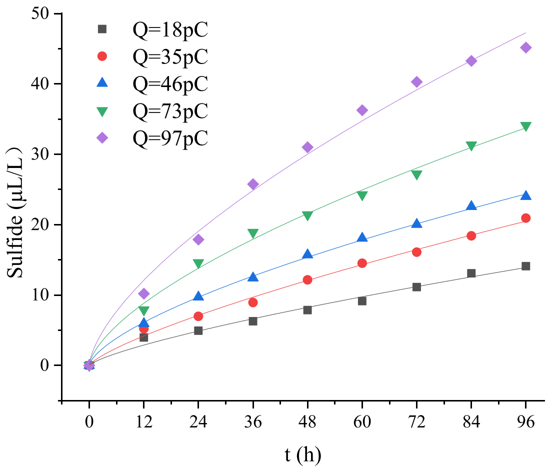

FIGURE 10. **Change curve of total sulfur content with time.**

so the content of SO_2 is relatively low. With the increase of discharge time, the growth rate is also very slow. When the discharge quantity increased, the content of SOF_2 increases rapidly, and the content of SOF_2 in the gas chamber is relatively high. Therefore, the content of SO_2 increases significantly. The relevant reaction process is as follows [21]:

$$SOF_2+H_2O \rightarrow SO_2 + 2HF \tag{16}$$

(e) The change characteristics of sulfide content with time

SO_2F_2, SOF_2, SOF_4 and SO_2 are the main sulfur decomposition products of SF_6 under PD. The total production of these four products can reflect the decomposition of SF_6 to some extent. Figure. 10 shows the change curve of the total content of these four sulfur products over time. It can be seen that with the extension of discharge time, the total content of these four sulfur-containing products increases linearly. Moreover, when the discharge increased, the slope of the change curve also changes significantly, which indicates that the total content of SO_2F_2, SOF_2, SOF_4 and SO_2 sulfur products is closely related to PD intensity.

3) THE CHANGE CHARACTERISTICS OF THE CONTENT OF CARBON CONTENT WITH TIME

(a) The change characteristics of CF_4 content with time

CF_4 is very stable. The C atoms in CF_4 are mainly released by electrode materials near PD region. The change curve of CF_4 content with time is shown in Fig 11. As can be seen from the figure, when the discharge quantity is low, the CF_4 content is relatively low. With the increase of discharge time, the CF_4 content increases very slowly.

This is because the release of C atom requires relatively high energy, and when PD intensity is low, the production of CF_4 is very low. With the increase of discharge quantity, the content of F atom and C atom increased. In comparison, the content of CF_4 generated is relatively low and the rising trend is not obvious. When the discharge quantity increased to more than 73pC, the increase of released C atoms is obvious, and the rising trend of CF_4 production is also very significant. However, because the number of C atoms is very small, and some C atoms will combine with O atoms to produce CO_2, the content of CF_4 has been relatively low.

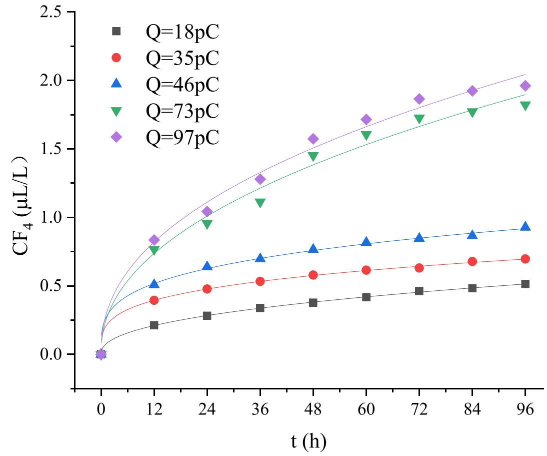

FIGURE 11. **Change curve of CF_4 content with time.**

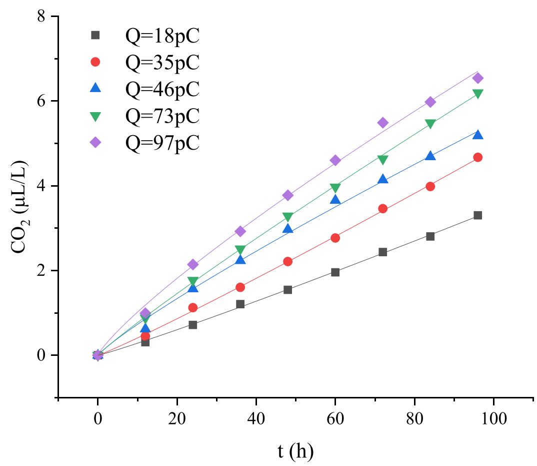

FIGURE 12. **Change curve of CO_2 content with time.**

(b) The variation characteristics of CO_2 content with time

The change curve of CO_2 content with time is shown in Figure. 12. With the increase of discharge quantity, CO_2 content increases steadily, but the overall content is still low. Moreover, under different discharge conditions, the slope of the curve of CO_2 content change with time is relatively close. With the increase of discharge quantity, the slope of the change curve of CO_2 content does not increase significantly. This is because few C atoms are excited from the electrode surface, and the shortage of C atoms limits the production of CO_2.

Compared with CF_4, the CO_2 content under the same condition is higher than CF_4, and the increase rate is also greater than CF_4, indicating that CO_2 is more easily generated than CF_4. This is because F atoms are more chemically active than O atoms, so the bond energy between the F atoms and S atoms is greater, and it takes more energy for electron collisions to break them apart, so O atoms are more likely to form and combine with C atoms to form CO_2. The relevant reaction process is as follows [21]:

$$C+2O \rightarrow CO_2 \tag{17}$$

$$C+4F \rightarrow CF_4 \tag{18}$$

IV. CONCLUSION

In this article, the correlation characteristics between the decomposition component of SF_6/N_2 gas mixture and PD intensity are studied through experiments, which lay a foundation for fault diagnosis and condition monitoring of SF_6/N_2 gas insulation equipment. The main conclusions are as follows:

(1) SF_6/N_2 gas mixture under PD can decompose to SOF_2, SO_2, SO_2F_2, SOF_4, CF_4, CO_2, NO, NO_2 and NF_3. The gas production laws of these decomposed components are quite different under different PD intensity.

(2) The content of NO_2 and (SO_2F_2+SOF_2+SOF_4+SO_2) increases linearly with discharge quantity, which can be used as the characteristic quantity to judge the whole process of PD. In short-term discharge, the content of SO_2F_2 increases greatly with time, which can be used as the characteristic quantity to judge the early PD.

(3) The content of SOF_2 and SOF_4 increases significantly with a rapid increase in PD intensity, which can be used as the characteristic quantities to judge severe PD.

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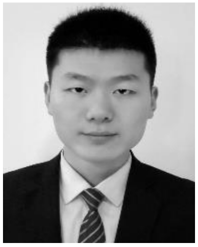

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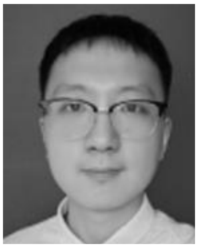

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