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AC Breakdown and Decomposition Characteristics of Environmental Friendly Gas $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$

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ABSTRACT $C_5F_{10}O$ (C5 perfluorinatedketone) has received extensive attention due to its great insulation and eco-friendly performance, which has the potential to replace SF_6 usage in power industries. In this paper, the power–frequency breakdown properties and discharge decomposition characteristics of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixtures are explored. It is found that the AC breakdown voltage of the $C_5F_{10}O$ gas mixtures increases gradually with both the gas pressure and the content of $C_5F_{10}O$. As the partial pressure of $C_5F_{10}O$ increases, the relative insulation strength increasing trend of the $C_5F_{10}O$ gas mixtures becomes less obvious with the increase in the gas pressure. The AC breakdown voltage of the $C_5F_{10}O$/Air gas mixture is higher than that of the $C_5F_{10}O/N_2$ gas mixture. In addition, the decomposition products of the $C_5F_{10}O$ gas mixtures are mainly CF_4, C_2F_6, C_3F_8, C_4F_{10}, and C_3F_7H. Under the same condition, the content of the CF_4 in $C_5F_{10}O$/Air gas mixture is higher than that of the $C_5F_{10}O/N_2$ gas mixture. The decomposition of the $C_5F_{10}O$/Air gas mixture after breakdown did not produce C_2F_4 and C_3F_6. CF_2O and CO_2 are not detected in the $C_5F_{10}O/N_2$ gas mixture. Moreover, the carbon precipitation on the electrodes' surface can be found for the $C_5F_{10}O/N_2$ gas mixture after 60 breakdown tests.

INDEX TERMS $C_5F_{10}O$ gas mixtures, AC breakdown, SF_6 alternative gas, decomposition component.

I. INTRODUCTION

Sulfur hexafluoride (SF_6) is widely used in medium-voltage (MV) and high-voltage (HV) equipment because of its excellent insulation and arc extinguishing characteristics [1]. But SF_6 is one of the most serious greenhouse gases and the call to replace it is getting louder in recent years. Policy makers has introduced strict laws to limit the application of SF_6 in power industry. To this end, researchers has conducted studies on SF_6 alternative gas such as N_2, air, CO_2 and SF_6 gas mixtures for forty years [2]–[7]. And studies on fluorocarbons gases including c-C_4F_8, CF_3I, C_4F_7N, $C_5F_{10}O$, $C_6F_{12}O$ have been ongoing [8-16]. Recent years, $C_5F_{10}O$ (C5 perfluorinatedketone) has received extensive attention due to its great insulation and eco-friendly performance. The AirPlus^{TM} introduced by ABB in 2016 used $C_5F_{10}O$ and technical air mixture as the insulating medium [17]. Although $C_5F_{10}O$ has a high liquefaction temperature (26.9°C) at normal pressure, its dielectric strength reaches twice that of SF_6. The Global Warming Potential (GWP) value of $C_5F_{10}O$ is only 1 and its atmospheric lifetime is about 15 days [18]–[20].

Over the past three years, scholars have carried out a series of research work on $C_5F_{10}O$. In terms of insulation strength, Safeguards *et al* tested and found that using $C_5F_{10}O$/Air gas mixture with a liquefaction temperature of −25°C can raise the rated voltage of the air switchgear from 12kV to 24kV [21]. Aints *et al* calculated the effective ionization coefficient of $C_5F_{10}O$ and believe that the gas mixture of $C_5F_{10}O$ and dry air has the potential to replace SF_6 in many MV and HV equipment [22]. Wang *et al* tested the power-frequency breakdown characteristics of $C_5F_{10}O/CO_2$ gas mixture under non-uniform electric field and pointed out that the insulation performance of the gas mixture can be effectively improved by increasing the content of $C_5F_{10}O$ [23]. Li *et al* found

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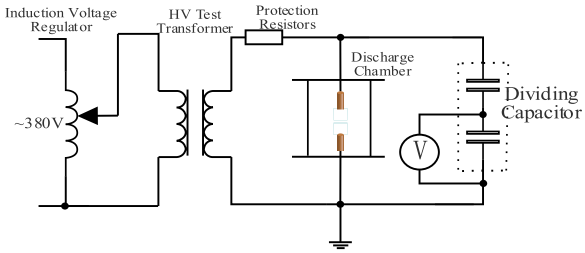


FIGURE 1. Principle of gas insulation performance test platform.

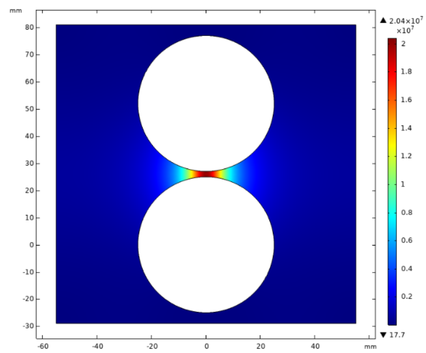


FIGURE 2. Simulation result of sphere-sphere electrodes.

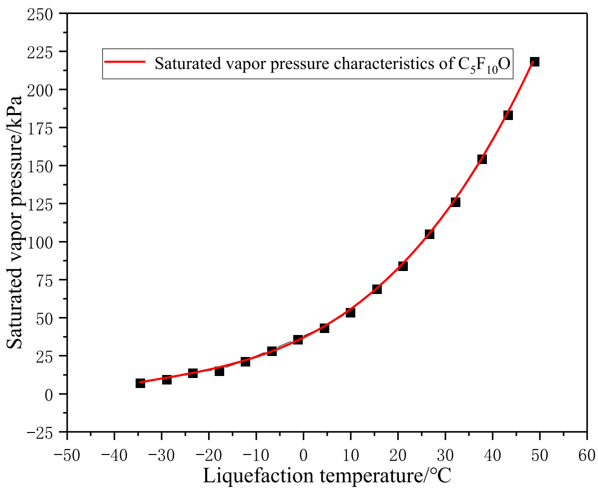


FIGURE 3. Different saturated vapor pressures of $C_5F_{10}O$ in $C_5F_{10}O$ gas mixtures and their corresponding liquefaction temperatures [18].

that the synergistic effect of $C_5F_{10}O/CO_2$ gas mixture is stronger than that of $C_5F_{10}O$/Air gas mixture [6]. As for the decomposition properties of $C_5F_{10}O$, Wang *et al* calculated the decomposition mechanism of $C_5F_{10}O$ based on the density functional theory (DFT) [24]. Our team has also carried out corresponding work and found that $C_5F_{10}O$ easily breaks carbon-carbon bonds to form $C_3F_7CO\bullet$ and $CF_3\bullet$ and $C_3F_7\bullet$ [25].

At present, there are many studies on $C_5F_{10}O$ gas mixtures, but most of them are carried out with CO_2 and dry air as buffer gas, and few report on the insulating properties of $C_5F_{10}O$ gas mixture with N_2 as buffer gas. Due to the similarity of composition between air and N_2, we mix $C_5F_{10}O$ with N_2 and dry air respectively to study the insulation properties of $C_5F_{10}O$ gas mixtures. The effects of gas pressure and partial pressure of $C_5F_{10}O$ ($C_5F_{10}O$ content) on the AC breakdown voltage of $C_5F_{10}O/N_2$ and $C_5F_{10}O$/Air gas mixtures are compared and analyzed, and the decomposition components of the gas mixtures are also detected. Relevant results can provide an important reference for the engineering application of $C_5F_{10}O$ gas mixtures.

II. METHOD

A. EXPERIMENTAL PLATFORM

The gas insulation performance test platform used in this paper is shown in Figure 1. The HV test transformer (100kV/0.5A) is used to provide the required power frequency high voltage. Protective resistance (10kΩ) is used to limit the short-circuit current during gap breakdown to prevent damage to the test transformer and the dividing capacitor is used to measure the actual voltage applied across the discharge chamber.

The maximum gas pressure that the chamber can withstand is 0.8MPa. The sphere-sphere electrodes made of brass are used to simulate the quasi-uniform electric field. Its radius is 25mm and the electrode gap is set to 2mm. The electric field distribution of the sphere electrodes simulated by COMSOL Multiphysics is shown in Figure 2. The Field Non-Uniform Coefficient is calculated to be 1.02 ($Emax = 2.04 \times 10^7$V/m, $Eav = 2 \times 10^7$V/m), which is accorded with quasi-uniform electric field conditions.

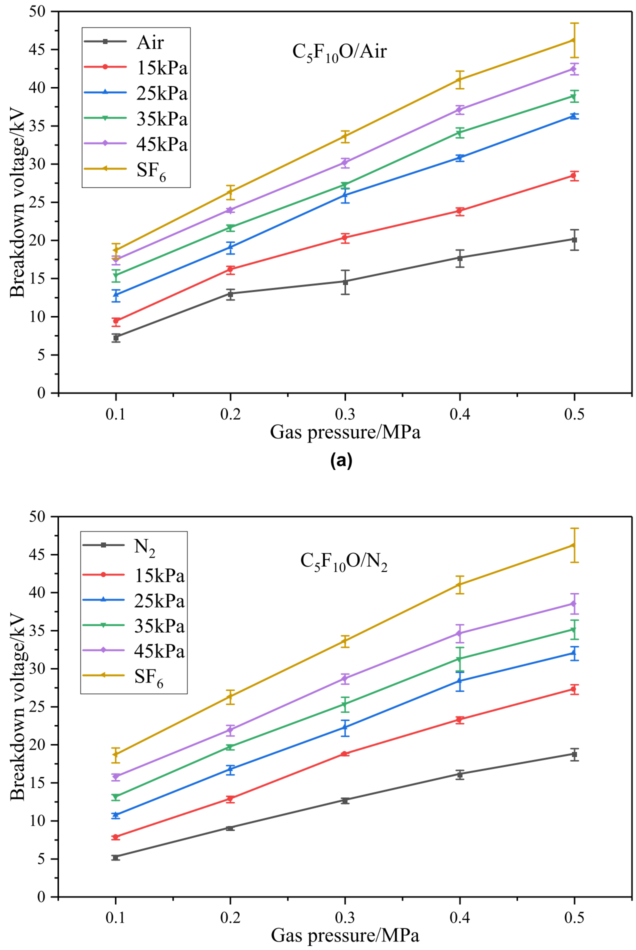
B. EXPERIMENTAL CONDITIONS

The liquefaction temperature of $C_5F_{10}O$ is higher than that of dry air and nitrogen. According to Dalton's law of partial pressure, they can be regarded as ideal gas and the partial pressure of a component in the gas mixture is the same as the gas pressure generated when the same container is individually filled, and the gas pressure is equal to the sum of the partial pressures of the constituent components, as shown in equation 1.

$$P_T = \sum_{i=1}^{n} p_i \tag{1}$$

where P_i and P_T are the partial pressure and gas pressure of each component. According to relevant reports, the saturated vapor pressure of $C_5F_{10}O$ at different liquefaction temperatures is shown in Figure 3 [15]. In order to observe the insulation properties of $C_5F_{10}O$ gas mixtures as comprehensively as possible, the partial pressure of $C_5F_{10}O$ is set to 0kPa, 15kPa, 25kPa, 35kPa, 45kPa, and the gas pressure is 0.1MPa, 0.2MPa, 0.3MPa, 0.4MPa, 0.5MPa in this paper. The insulating properties of pure SF_6 under the same conditions are also tested.

The discharge chamber is cleaned before the test. The chamber is pumped to vacuum, then filled with the buffer gas and pumped to vacuum again. This process is repeated for three times to ensure that there is no impurity in the



(a)

(b)

FIGURE 4. **(a) Relation between breakdown voltage and gas pressure of $C_5F_{10}O$/Air gas mixture. (b) Relation between breakdown voltage and gas pressure of $C_5F_{10}O/N_2$ gas mixture.**

chamber. Due to the low saturated vapor pressure of $C_5F_{10}O$, and according to Dalton's law of partial pressure, a certain amount of $C_5F_{10}O$ should be charged firstly according to the set partial pressure ratio, and finally the chamber is filled with buffer gas to the set value.

In order to ensure the rigor of the test and the correctness of the data, a single set of each data is obtained from the average of ten test values. The stepwise boost method is used to apply the AC voltage to the electrode. Test interval is set to 5min to ensure the dielectric strength of the gas in the chamber restored maximally. Allow the chamber to stand for 24 hours after each inflation to ensure the gases mixed evenly.

III. RESULTS AND DISCUSSION

A. ANALYSIS OF INSULATION PERFORMANCE OF $C_5F_{10}O$ GAS MIXTURES

Figure 4 shows the relationship between AC breakdown voltage and pressure of $C_5F_{10}O$ gas mixtures, pure SF_6, nitrogen and dry air. The breakdown voltage of all kinds of gas mixtures increases with the increase of gas pressure. In fact, the average free path of the electrons will decrease with the increase of gas pressure, and the kinetic energy of the electrons in the electric field will be less, thereby reducing the probability of collision ionization. Thus, the breakdown voltage increases with the increase of gas pressure.

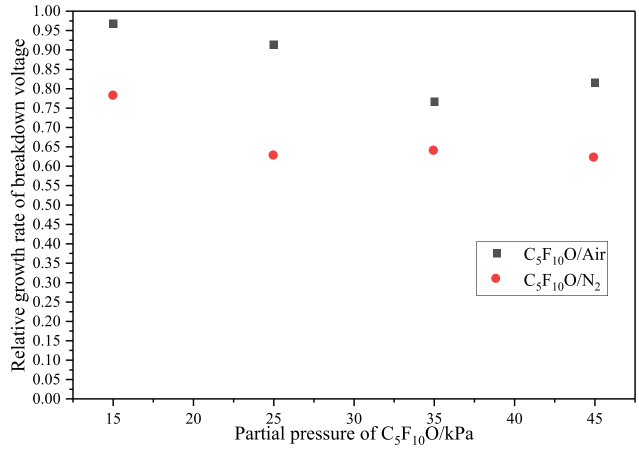


FIGURE 5. **Effect of gas pressure on breakdown voltage of $C_5F_{10}O$ gas mixtures at high gas pressure.**

When the gas pressure is in the range of 0.1-0.4MPa, the breakdown voltage of each gas mixture increases linearly with the gas pressure. While the increase rate of the AC breakdown voltage of $C_5F_{10}O$ gas mixtures and SF_6 are reduced, showing a certain saturation trend at gas pressures higher than 0.4MPa.

On the other hand, to further investigate the effect of gas pressure on the breakdown voltage of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixture under high gas pressure conditions, define the relative growth rate of breakdown voltage at high gas pressure V_H.

$$V_H = \frac{\Delta U_H}{\Delta U_L} \tag{2}$$

in which ΔU_H is the rising rate of breakdown voltage from 0.4MPa to 0.5MPa, ΔU_L is the rising rate of gas breakdown voltage of 0.1-0.4MPa, the unit of kV/MPa is applied. The relative growth rate of the breakdown voltage of gas mixtures at high gas pressure obtained (See Figure 5). We can find that the V_H values at each partial pressure of $C_5F_{10}O$ are less than 1, indicating that the increase rate of breakdown voltage of $C_5F_{10}O$ gas mixtures at 0.4-0.5MPa are lower than those of 0.1-0.4MPa. After the gas pressure reaches higher than 0.4MPa. The relative growth rate of breakdown voltage of $C_5F_{10}O$/Air gas mixture is higher than that of $C_5F_{10}O/N_2$ gas mixture, indicating that the breakdown voltage of $C_5F_{10}O$/Air gas mixture is less affected by gas pressure.

In addition, when considering a larger partial pressure of $C_5F_{10}O$, it is promising to replace SF_6 at low filling gas pressure by slightly increasing the gas pressure of the $C_5F_{10}O$ gas mixtures. For example, when the gas pressure is 0.2MPa and the partial pressure of $C_5F_{10}O$ is 25kPa, the breakdown voltage of $C_5F_{10}O$/Air gas mixture is 0.72 times that of SF_6 at 0.2MPa. When the gas pressure is increased to

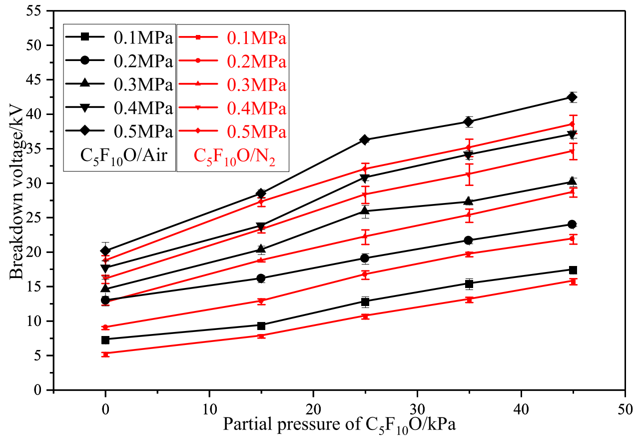


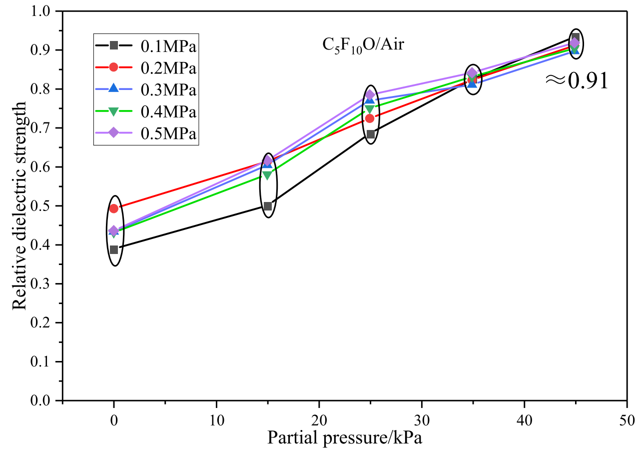
FIGURE 6. Effect of partial pressure of $C_5F_{10}O$ on breakdown voltage of $C_5F_{10}O$ gas mixtures.

0.3MPa, the breakdown voltage of $C_5F_{10}O$/Air gas mixture is 0.98 times that of SF_6 at 0.2MPa. Under the above two conditions, the breakdown voltage of $C_5F_{10}O/N_2$ gas mixture is 0.63 times and 0.84 times that of SF_6 at 0.2MPa, respectively.

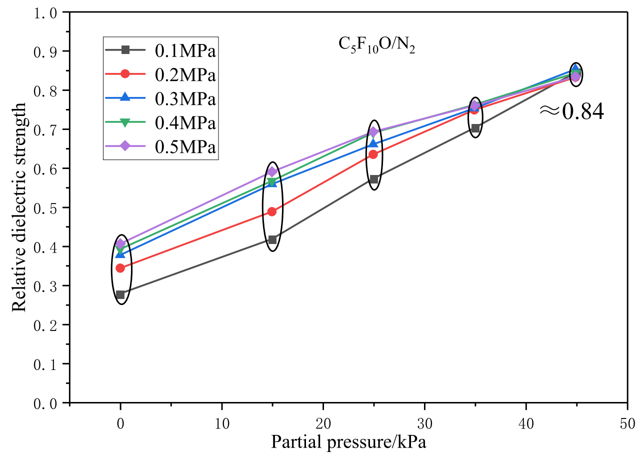
Figure 6 shows the relationship between the breakdown voltage of $C_5F_{10}O$ gas mixtures and the partial pressure of $C_5F_{10}O$. As the partial pressure of $C_5F_{10}O$ increases, the breakdown voltage of $C_5F_{10}O$ gas mixtures increases. Actually as a strong electron negative substance, $C_5F_{10}O$ has a large cross-section in the low energy range. The negative ions formed after the adsorption of electrons have less kinetic energy and are easily combined with positive ions in the electric field, so that the charged particles in the electric field are greatly reduced.

Since the insulation strength of the dry air is greater than that of nitrogen, the increase in breakdown voltage of $C_5F_{10}O/N_2$ gas mixture at a partial pressure of 15kPa is more obvious than that of $C_5F_{10}O$/Air gas mixture. For example, at 0.1MPa, the breakdown voltage of $C_5F_{10}O/N_2$ gas mixture is only 7.76kV, whereas the breakdown voltage of $C_5F_{10}O$/Air gas mixture is 9.25kV, but the breakdown voltage of N_2 is increased by 51% after 15kPa $C_5F_{10}O$ is added, and the breakdown voltage of dry air is increase by 29% under the same condition. However, as the partial pressure of $C_5F_{10}O$ increases, the increase rate of the breakdown voltage of $C_5F_{10}O$/Air gas mixture is similar to that of $C_5F_{10}O/N_2$ gas mixture. But the breakdown voltage of $C_5F_{10}O$/Air gas mixture is greater than that of $C_5F_{10}O/N_2$ gas mixture under each partial pressure.

Figure 7 shows the relative dielectric strength of $C_5F_{10}O$ gas mixtures to SF_6. It can be found that the dielectric strength of $C_5F_{10}O$ gas mixtures relative to SF_6 increase with the $C_5F_{10}O$ content in the gas mixtures. However, when the partial pressure of $C_5F_{10}O$ is high enough, the relative dielectric strength of the $C_5F_{10}O$ gas mixtures at each gas pressure will approach a certain value (i.e. $C_5F_{10}O$/Air gas mixture is about 0.91, $C_5F_{10}O/N_2$ gas mixture is about 0.84). That is, the insulation strength of $C_5F_{10}O$ gas mixtures under the same gas pressure will always be lower than that of SF_6, and



(a)



(b)

FIGURE 7. (a) Relative dielectric strength of $C_5F_{10}O$/Air gas mixture at different partial pressure of $C_5F_{10}O$. (b) Relative dielectric strength of $C_5F_{10}O/N_2$ gas mixture at different partial pressure of $C_5F_{10}O$.

with the increase of partial pressure of $C_5F_{10}O$, the promotion effect of the insulation strength becomes less obvious with the increase of gas pressure.

When the partial pressure of $C_5F_{10}O$ reached 45kPa, the liquefaction temperature of the gas mixtures are as high as 5.56°C. Thus this kind of gas mixtures have lost the engineering application potential. In addition, the breakdown voltage of $C_5F_{10}O$ gas mixtures with 15kPa $C_5F_{10}O$ (the liquefaction temperature is -17.78°C) reach 50% of SF_6. Therefore, it is recommended to select a gas mixture with low partial pressure of $C_5F_{10}O$ for use in indoor low-voltage equipment.

B. DECOMPOSITION COMPONENTS OF $C_5F_{10}O$ GAS MIXTURES

The difference between the two gas mixtures is oxygen. We explored the similarities and differences between them in terms of decomposition characteristics. The gas samples of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixtures with 15kPa $C_5F_{10}O$ after 60 times breakdown tests at 0.2MPa are collected and detected by Gas Chromatography Mass

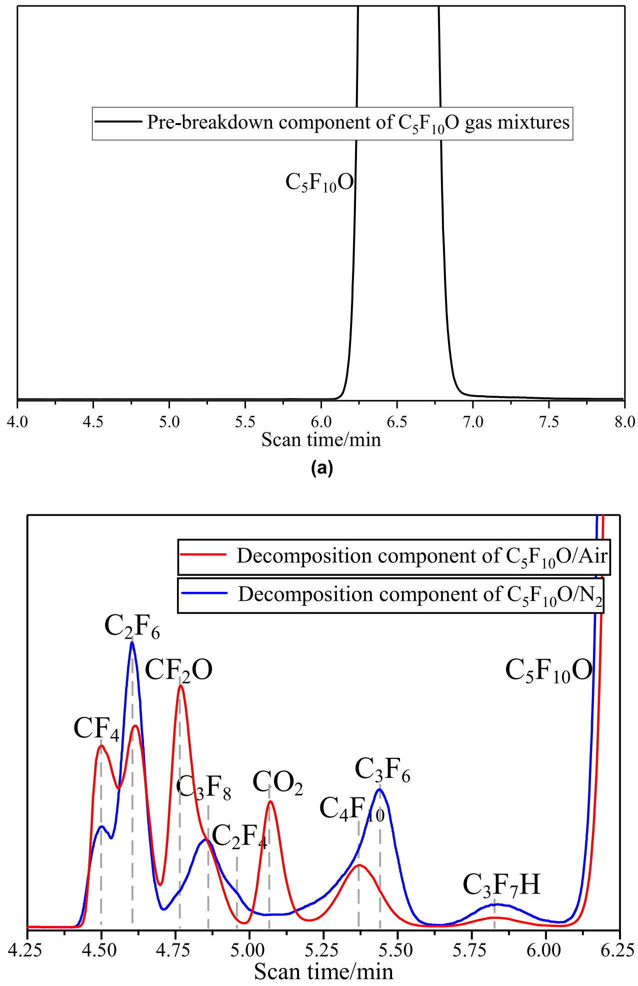


FIGURE 8. **(a) GC/MS scanning chart of $C_5F_{10}O$ gas mixtures before 60 breakdowns. (b) GC/MS scanning chart of $C_5F_{10}O$ gas mixtures after 60 breakdowns.**

TABLE 1. **Components of $C_5F_{10}O$ gas mixtures after 60 breakdowns.**

Components	$C_5F_{10}O$/Air	$C_5F_{10}O/N_2$	Electric strength (re SF_6)	GWP
CF_4	exist	exist	0.40[26]	6300[28]
C_2F_6	exist	exist	0.73[26]	9200[27],12500[28]
CF_2O	exist	not exist	-	-
C_3F_8	exist	exist	0.86[26]	7000[27]
C_2F_4	not exist	exist	-	-
CO_2	exist	not exist	0.35[26]	1
C_4F_{10}	exist	exist	1.21[26]	7000[27]
C_3F_6	not exist	exist	1.02[26]	8000[27]
C_3F_7H	exist	exist	-	-

Spectrometer (GC-MS). The Scan method is used and the composition of gas samples is determined according to the National Institute of Standards and Technology (Nist14.0) standard chromatography database. (See Table 1).

According to the composition results given above, the decomposition components of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixtures are not exactly the same. No CF_2O or CO_2 is detected for $C_5F_{10}O/N_2$ gas mixture after breakdown, and C_2F_4 and C_3F_6 are not detected for $C_5F_{10}O$/Air gas mixture after breakdown. The content of CF_4 in $C_5F_{10}O/N_2$ gas mixture is lower than that of C_2F_6, whereas the ratio of CF_4 to C_2F_6 in $C_5F_{10}O$/Air gas mixture is close to 1 and the content of CF_4 is higher. In addition, the content of C_3F_7H in $C_5F_{10}O$/Air gas mixture is also lower than that of $C_5F_{10}O/N_2$ gas mixture.

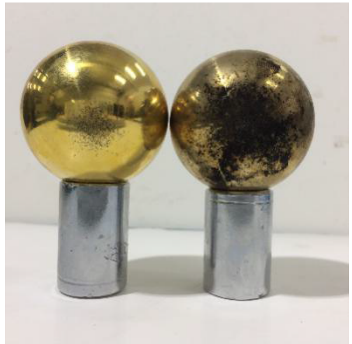


FIGURE 9. **Comparison of spherical electrode surface after 60 breakdowns of $C_5F_{10}O$ gas mixtures.**

Actually, $C_5F_{10}O$/Air gas mixture can be regarded as replacing 38.66kPa of nitrogen in $C_5F_{10}O/N_2$ gas mixture with oxygen under the experimental conditions. Obviously, the replacement of this part of oxygen leads to different insulation strength of the gas mixtures. The difference in the type and relative content of the decomposition components is also attributed to this. The presence of oxygen makes it difficult for C_2F_4 and C_3F_6 to exist stably, for such molecules containing an unsaturated C=C Bond. At the same time, the relative content of CF_4 and C_2F_6 changes, which indicates that the formation of small molecules such as CF_4 is promoted after the oxygen is added. And the decrease of C_3F_7H indicates that the formation of macromolecules is inhibited with the presence of oxygen. In addition, we found that the electrodes of $C_5F_{10}O/N_2$ gas mixture after breakdown precipitated black solid particles, while the electrode used in $C_5F_{10}O$/Air gas mixture (Figure 9) has no carbon particle presence. Obviously, oxygen and carbon attached to the surface of the electrode cannot coexist, which may react to generate CO_2. That is to say, the addition of oxygen can impede the precipitation of solid particles. The generation of CF_2O is also related to the addition of oxygen which may oxidize the fluorocarbons to a certain extent.

Overall, the difference between the discharge decomposition components of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixtures is the presence or absence of CF_2O, C_2F_4 and C_3F_6. Considering the safety aspect of using $C_5F_{10}O$ gas mixture, CF_2O (Carbonyl fluoride, CAS: 353-50-4) has a 50% lethal concentration (LC50, 4h) of only 270 mg/m^3 (rat inhalation), which is a highly toxic substance. In addition, CF_2O has a strong stimulating effect on the respiratory mucosa. Acute poisoning can cause chemical pneumonia and pulmonary edema. The LC50 (4h, rat inhalation) of C_2F_4 (Tetrafluoroethylene, CAS:

116-14-3) is 164000 mg/m^3, and C_3F_6 (Hexafluoropropylene, CAS: 116-15-4) has an LC50 (4h, rat inhalation) of 11200 mg/m^3, both of which are low-toxic substances. The influence of toxicological properties of the decomposition components of $C_5F_{10}O$ gas mixture on equipment and personnel should be considered.

However, it should ensure that there are no conductive particles inside the equipment to prevent the uniformity of the electric field from being affected and avoid the internal defects being further aggravated by the presence of conductive particles. Thus, $C_5F_{10}O$/Air gas mixture has much more potential for application than $C_5F_{10}O/N_2$ gas mixture.

IV. CONCLUSION

In this paper, the AC breakdown characteristics and decomposition properties of $C_5F_{10}O/N_2$, $C_5F_{10}O$/Air gas mixtures are tested. The influence of gas pressure and $C_5F_{10}O$ content on the insulation properties of $C_5F_{10}O$ gas mixtures is analyzed. Several conclusions can be obtained as follows:

1) The AC breakdown voltage of $C_5F_{10}O$/Air gas mixture is higher than that of $C_5F_{10}O/N_2$ gas mixture under the same conditions. The breakdown voltage of $C_5F_{10}O$/Air gas mixture is less affected by gas pressure. When the partial voltage of $C_5F_{10}O$ is greater than 15kPa, the breakdown voltage of $C_5F_{10}O$/Air gas mixture increases with the partial voltage of $C_5F_{10}O$ at a rate similar to that of $C_5F_{10}O/N_2$ gas mixture.
2) The insulation strength of gas mixtures under low partial pressure of $C_5F_{10}O$ has reached 0.5 times of SF_6, increasing the partial pressure of $C_5F_{10}O$ or the gas pressure of gas mixtures can increase the insulation strength of $C_5F_{10}O$ gas mixtures. $C_5F_{10}O$ gas mixtures have the potential to replace SF_6 using in indoor low-voltage electrical equipment.
3) As the partial pressure of $C_5F_{10}O$ increase, the relative insulation strength of $C_5F_{10}O$ gas mixtures is not obvious with the increase of gas pressure. The relative dielectric strength of the $C_5F_{10}O$ gas mixtures at each gas pressure will approach a certain value ($C_5F_{10}O$/Air gas mixture is about 0.91, $C_5F_{10}O/N_2$ gas mixture is about 0.84) when the partial pressure of $C_5F_{10}O$ is high enough.
4) The decomposition characteristics of $C_5F_{10}O$/Air and $C_5F_{10}O/N_2$ gas mixtures are different. The presence of oxygen causes small molecules such as CF_4 be easy to generate. CO_2 and CF_2O are also produced with the addition of oxygen, while C_2F_4 and C_3F_6 disappears. $C_5F_{10}O/N_2$ gas mixture after repeated breakdown could precipitate solid particles on the electrodes surface. The addition of oxygen could prevent this, indicating that $C_5F_{10}O$/Air gas mixture has much more potential for application than $C_5F_{10}O/N_2$ gas mixture.

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