

Influence of trace H_2O and O_2 on SF_6 decomposition products under arcing conditions in electric power equipment

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Abstract: SF_6 has been widely used as an insulating and arc extinguishing medium in electric power equipments. Detection of gas decomposition products is an important means for condition monitoring and fault diagnosis. Trace H_2O and O_2 have a significant influence on the species and concentrations of SF_6 decomposition products. It is important to explore the influence mechanism of trace H_2O and O_2 on SF_6 decomposition products under arcing conditions. A series of SF_6 decomposition tests were carried out on a 40.5 kV SF_6 circuit breaker, and a gas chromatograph and an electrochemical sensor were used to measure decomposed components. First, the H_2O content remained constant, and the O_2 content and arcing energy changed in the tests. It has been found that the decomposition products of SF_6 are SOF_2 , SO_2 , CO , CO_2 , CF_4 , C_2F_6 and C_3F_8 . Then, the O_2 content remained constant, and the H_2O content changed. The decomposition products are mainly SOF_2 , SO_2 , CO and CO_2 . Concentrations of all these decomposition products increase first and then tend to be stable slowly over time, but change differently with the increase of H_2O and O_2 contents, because H_2O and O_2 play different roles in the formation process of each decomposition characteristic components.

1 Introduction

SF_6 is widely used in electric power equipment because of its excellent insulating performance and arc-quenching performance [1–3]. The SF_6 circuit breaker has advantages of small volume, reliable operation, long maintenance cycle, and so on. The operating state of the SF_6 circuit breaker plays a decisive role in the safe and stable operation of the power grid.

Many studies have shown that the electric arc can cause SF_6 decompose into SF_x ($x = 1, 2, 3, 4, 5$). SF_x can react with H_2O , O_2 , insulation materials, and metallic materials in the circuit breaker and eventually produce SOF_2 , SO_2 , SO_2F_2 , CO , CO_2 , CF_4 , C_2F_6 , Cu_2S , H_2S , HF , and so on [4–6]. On the one hand, some corrosive decomposition products (e.g. HF and H_2S) will react with the insulation materials and metallic materials in the circuit breaker, which seriously threatens the stable operation of the circuit breaker. On the other hand, some characteristic decomposition products (e.g. SO_2 , CF_4 , and CO) are closely related to the internal state of the SF_6 circuit breaker. Therefore, some faults in the SF_6 circuit breaker could be monitored and diagnosed by detecting SF_6 decomposition components and their content variation [7–9]. So it is important to research the decomposition products under arcing conditions [10].

Leeds *et al.* studied the decomposition components of the SF_6 gas in the circuit breaker. They found that the decomposition components can be absorbed by alumina. Boudene *et al.* studied the decomposition products in detail under the condition of 60 kV voltage, 4.5 kA current, and 40–80 ms arcing time. They found the gas production rates of SOF_2 and SO_2F_2 , and arc energy was almost linear [11]. Belmadani *et al.* studied the decomposition components in two types of Alstom circuit breakers. They found that the main stable products are SOF_2 , SO_2 , SO_2F_2 , and CF_4 [5, 6].

However, the decomposition characteristics of SF_6 not only relate to the degree of arcing energy and current but also relate to trace H_2O and O_2 . Most previous studies only focused on the effects of different current and different arc energy on

decomposition products. In addition, the means of testing are very limited [12–14]. So the practical application of the decomposed components analysis (DCA) method has great difficulties. It is urging to research the influence of trace H_2O and O_2 on SF_6 decomposition products under arcing conditions.

In this paper, a series of SF_6 decomposition tests were carried out on a 40.5 kV SF_6 circuit breaker, and the gas chromatograph and electrochemical sensor were used to measure decomposed components.

2 Experimental platform

2.1 Arcing experiment

The breaking tests of the 40.5 kV SF_6 circuit breaker were carried out using a high-voltage synthetic circuit. As shown in Fig. 1. L_1 and C_1 form the oscillation circuit for the current source to provide the short-circuit current. The oscillation frequency is 50 Hz. L_2 and C_2 form the oscillation circuit for the recovery voltage applied to the circuit breaker.

L_1 and L_2 are the inductors of the current source and voltage source, respectively. C_1 and C_2 are the capacitors of current source and voltage source. K_1 is the make switch. K_2 is the arc holding switch. K_3 is the auxiliary circuit breaker. SP is the test circuit breaker. R_2 is the arc holding resistance. R_{01} , R_{02} , C_{01} , and C_{02} are the thermostatic radiator valve adjusting elements. F , F_1 , and F_2 are the current dividers. FV is the voltage divider. D is the gap. The parameters of the SF_6 circuit breaker are shown in Table 1.

2.2 Decomposition product detection method

At present, there are many ways to detect the decomposition products in the laboratory and in the field. The electrochemical sensor can detect SO_2 , H_2S , and CO accurately, and the accuracy can reach the parts per million (ppm) level. It is very suitable for field detection. The gas chromatograph can detect SO_2F_2 , SOF_2 , CF_4 , CO_2 , CO , SO_2 , H_2S , and so on in SF_6 gas. The accuracy can

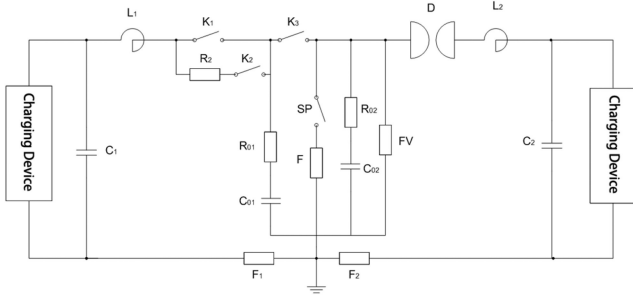


Fig. 1 Synthetic circuit for circuit breaker testing

Table 1 Parameters of the SF₆ circuit breaker

Rated voltage	Rated current	Rated short-circuit breaking current	Operation frequency	Rated operation pressure
40.5 kV	2 kA	31.5 kA	50 Hz	0.6 MPa

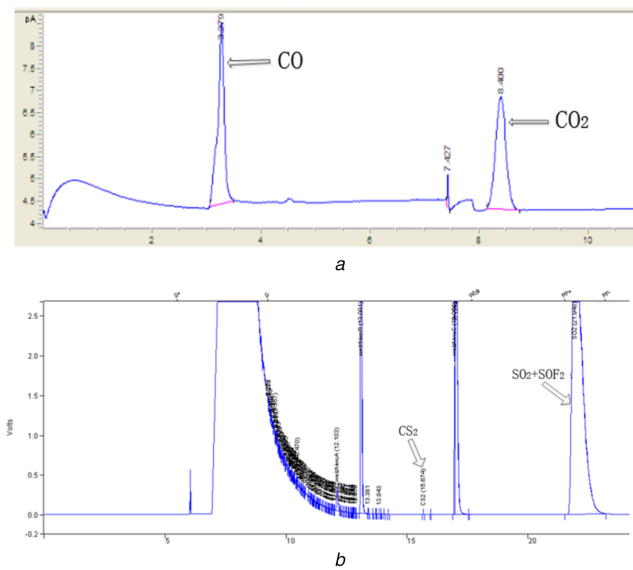


Fig. 2 Typical gas chromatogram

(a) Typical chromatogram of FID, (b) Typical chromatogram of PFPD

reach the ppm level. It is very suitable for laboratory detection. In this study, both gas chromatograph and electrochemical sensor are used to detect the decomposition products. The gas chromatograph is equipped with a hydrogen flame ionisation detector (FID) and pulsed flame photometric detector (PFPD) to detect decomposition products. FID can detect CO, CO₂, CF₄, and C₂F₆ in SF₆, and PFPD can detect CS₂, SO₂, and SOF₂. The typical chromatograms are shown in Fig. 2.

3 Results and discussions

3.1 Mechanisms of decomposition of SF₆ in the arc

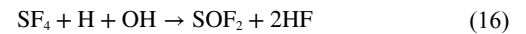
During the arc burning, the high temperature of the arc will make SF₆ decompose into SF₄, SF₂, and S. When there are trace O₂ and H₂O in SF₆, the arc will also decompose H₂O and O₂ into O and OH. The reaction processes are as follows:



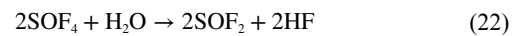
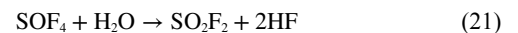
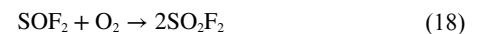
At the same time, under the high temperature of the arc, SF₆ and O will react with the insulating material (polytetrafluoroethylene) of the nozzle to produce CF₄, C₂F₆, and C₃F₈. The reaction processes are as follows:



In a very short time (about 10⁻⁵ s) after the arc extinguished, most of SF₄, SF₂, and S will recombine to SF₆. At the same time, O, OH, and H produced during the arcing time are also involved in the reorganisation of SF_x and F. The reaction processes are as follows:



As the temperature in the circuit breaker drops to the normal temperature, some of the non-compound SF_x and decomposition products (SOF₄ and SOF₂) will continue to react slowly with the H₂O and O₂ in the chamber. The reaction processes are as follows:



3.2 Influence of trace O₂ on SF₆ decomposition products

Under different O₂ content, many sets of breaking experiments were carried out. The O₂ contents in SF₆ are 0, 1, 1.6, and 2.2%. The arc currents are about 4, 8, and 12 kA. After breaking, the decomposition products are mainly SO₂, SOF₂, CF₄, C₂F₆, C₃F₈, CO, and CO₂. It is worth noting that when the current reaches 14.6 kA, the H₂S can be detected.

Fig. 3 shows the variation of the SO₂ content with time when the arc current is 11 kA with a different O₂ content. It can be seen that the SO₂ content increases rapidly in the first hour, and then tend to be stable. When the O₂ contents are 0, 1, 1.6, and 2.2%, the SO₂ contents are 11.6, 15.0, 16.4, and 18.2 μL/L at 8.5 h after breaking. So it can be seen that O₂ promotes the production of SO₂. The main reason is that the increase of the O₂ content promotes reaction (4) and (12), and thus promotes reaction (19), which eventually leads to the increase of the SO₂ content.

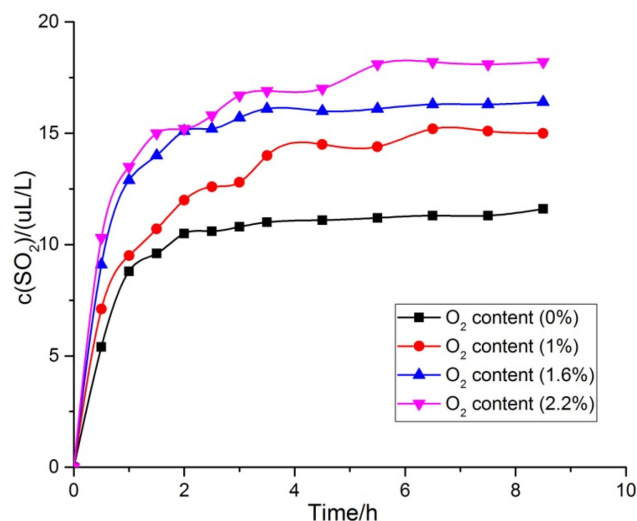


Fig. 3 Effect of the O_2 content on SO_2 concentration

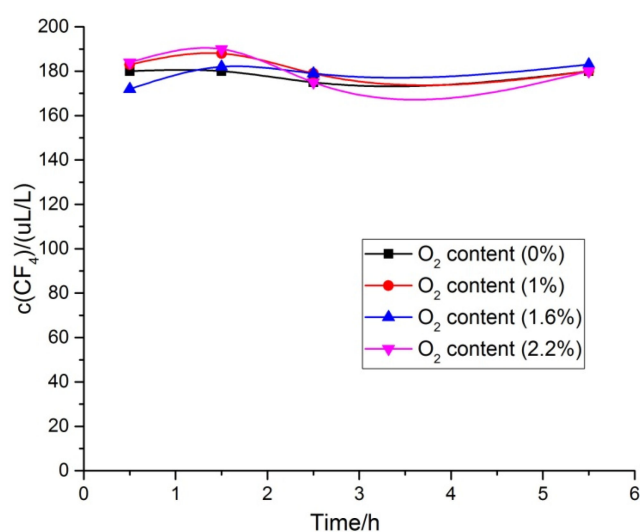


Fig. 4 Effect of the O_2 content on CF_4 concentration

Fig. 4 shows the variation of the CF_4 content with time when the arc current is 11 kA with a different O_2 content. It can be seen that the CF_4 content hardly changes with time, and the O_2 content has almost no effect on CF_4 . The main reason is that the reaction (6) does not involve the O atom.

Fig. 5 shows the variation of the SO_2 content with arc energy when the O_2 content is 2%. It can be seen that there is a linear relationship between the concentration of SO_2 and the arc energy. By detecting the concentration of SO_2 inside the circuit breaker, the arc energy can be evaluated.

3.3 Influence of trace H_2O on SF_6 decomposition products

Under different concentrations of H_2O , many sets of breaking experiments were carried out. The concentrations of H_2O in SF_6 are 56, 503, 790, and 1540 $\mu\text{L/L}$. The arc currents are ~ 4 , 8, and 12 kA. After breaking, the decomposition products are mainly SO_2 , SOF_2 , CO , and CO_2 .

Fig. 6 demonstrates the variation of the SO_2 content with time when the arc current is ~ 12 kA with a different H_2O content. It can be seen that the SO_2 content increases rapidly first, and then tends to be stable. With the concentration of H_2O increases, the time for the SO_2 content to reach stability increases. When the concentrations of H_2O are 56, 503, 790, and 1540 $\mu\text{L/L}$, the concentrations of SO_2 are 11.7, 12.8, 15.7, and 18.3 $\mu\text{L/L}$ at 8 h after breaking. So it can be seen that H_2O promotes the production of SO_2 . The main reason

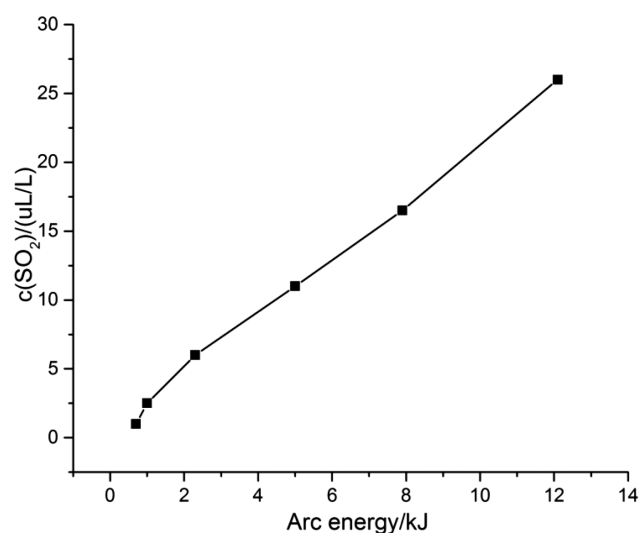


Fig. 5 Effect of arc energy on SO_2 concentration

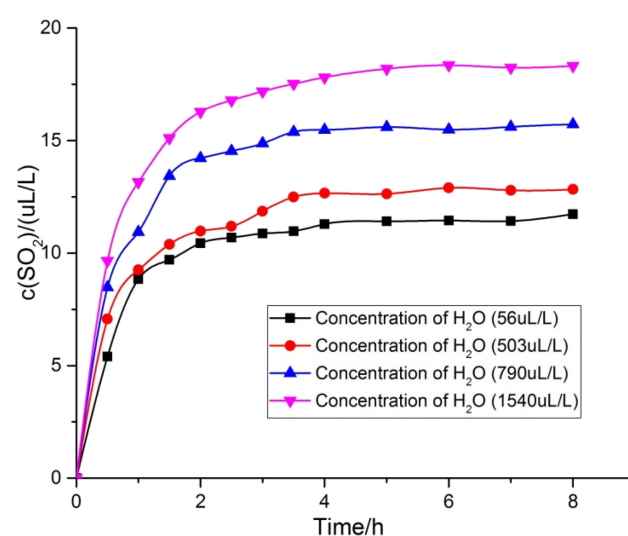


Fig. 6 Effect of the concentration of H_2O on SO_2 concentration

is that the increase of the concentration of H_2O promotes reactions (5), (12), (16), and (20), and then promotes reaction (19), which eventually leads to the increase of the SO_2 content.

Fig. 7 shows the variation of the CO content with time when the arc current is ~ 12 kA with a different H_2O content. It can be seen that the CO content increases rapidly in the first hour, and then tends to be stable. When the concentrations of H_2O are 503, 790, and 1540 $\mu\text{L/L}$, the concentrations of CO are 2.8, 6.9, and 11.7 $\mu\text{L/L}$ at 8 h after breaking. So it can be seen that H_2O promotes the production of CO . The main reason is that the increase of the concentration of H_2O promotes reaction (5), and then promotes reaction (9), which eventually leads to the increase of the CO content.

Fig. 8 is the variation of the SO_2 and CO contents with time when the concentration of H_2O is about 800 $\mu\text{L/L}$ with different arc energy. It can be seen that the concentrations of SO_2 and CO show the same rule with the arc energy.

4 Conclusion

In this study, a series of SF_6 decomposition tests under arcing conditions were carried out on a 40.5 kV SF_6 circuit breaker, and a gas chromatograph and an electrochemical sensor were used to measure decomposed components.

When the O_2 content changes, the decomposition products are mainly SO_2 , SOF_2 , CF_4 , C_2F_6 , C_3F_8 , CO , and CO_2 . The concentration of SO_2 increases with the O_2 content, and the

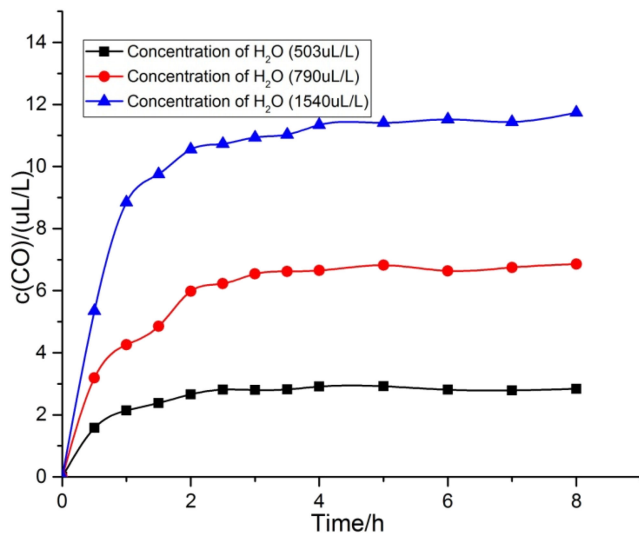


Fig. 7 Effect of the concentration of H_2O on CO concentration

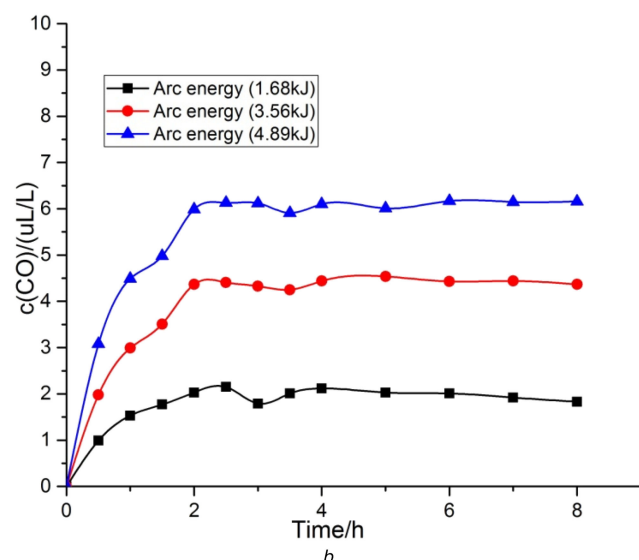
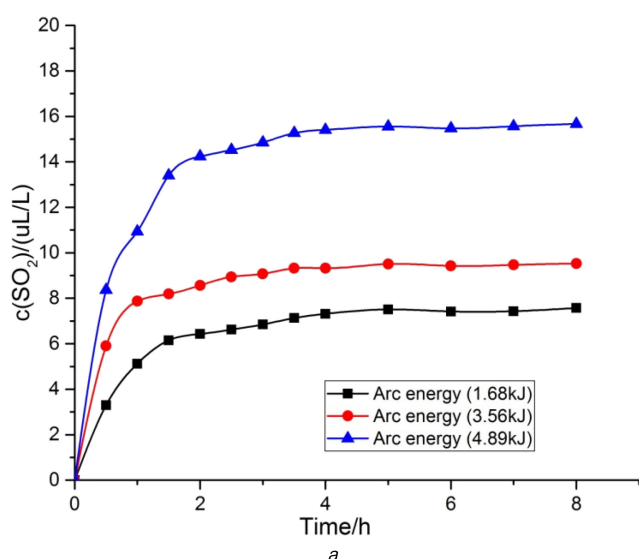


Fig. 8 The effect of arc energy on SO_2 and CO concentration

(a) The effect of arc energy on SO_2 concentration, (b) The effect of arc energy on CO concentration

concentration of CF_4 hardly changes with the O_2 content. The concentration of SO_2 and the arc energy show a linear relationship.

When the H_2O content changes, the decomposition products are mainly SO_2 , SOF_2 , CO , and CO_2 . The concentrations of SO_2 and CO increase with the H_2O content. The relationship between SO_2 and arc energy is similar to that of CO and arc energy.

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