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Research Progress on Synergistic Effect between Insulation Gas Mixtures

Su Zhao and Dengming Xiao

Abstract

Synergetic effect is a special gas discharge phenomenon among insulating gas mixtures, which has important reference value for gas selection of future gas-insulated power equipment. The research progress and investigation methods of synergistic effect and insulation characteristics of different gas mixtures at home and abroad are reviewed in this chapter. The synergistic effect between different kinds of gas mixtures including SF₆ gas mixtures and some new insulation gases such as c-C₄F₈, CF₃I, and C₄F₇N is presented. Combined with the results of multiple studies, it can be seen that the synergistic effect of the gas mixture has a certain relationship with the electronic transport parameters and discharge patterns. Besides, the synergistic effect of the same gas mixture may change with the change of external conditions such as gas pressure, voltage type, and electrode distance.

Keywords: gas discharge, synergistic effect, gas mixture, insulation, environmental friendly gas

1. Introduction

With the continuous development of power industry, gas-insulated power equipment has been used more and more widely in electrical transmission system. Gas-insulated power equipment mainly includes gas-insulated transformer (GIT), gas-insulated transmission line (GIL), and gas-insulated switchgear (GIS). These gas-insulated equipment are noncombustible, nonexplosive, safe, and stable and have long maintenance period [1]. At present, SF₆ gas is the most widely used gas in power equipment, which has excellent insulation performance and arc extinguishing ability. As early as the 1940s, SF₆ gas has been used as insulation gas in power equipment [2]. Since the 1970s, researchers have studied the use of gas mixture including SF₆ and some buffer gases such as N₂, CO₂, Ar, He, air, etc. to replace pure SF₆ as the insulation medium [3–5]. With further study, researchers found that the insulation characteristics of gas mixtures containing SF₆ gas did not increase linearly according to the mixing ratio of SF₆, and the electrical strength of the mixture was higher than the weighted average of the electrical strength of the two gas components. In 1980, Wootton and Chantry first used synergism to describe this phenomenon [6]. In the study of synergistic effect, scholars have found that there are also super synergistic effect and negative synergistic effect, which are shown in **Figure 1**.

Suppose that the composition of gas mixture is gas 1 and gas 2, the breakdown voltage of gas 1 is U_1 , the breakdown voltage of gas 2 is U_2 , and $U_1 > U_2$, the

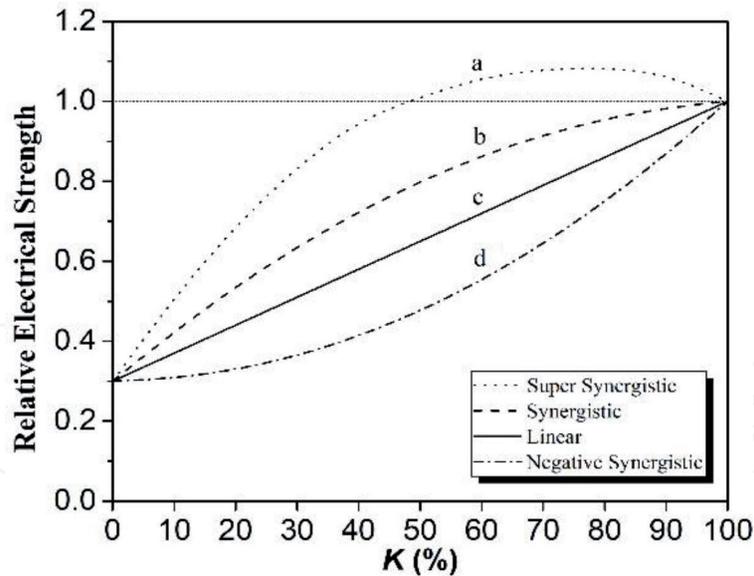


Figure 1.
Types of synergistic effect.

breakdown voltage of gas mixture is U_m , and K is the mixing ratio of gas 1 in the gas mixture. For super synergistic effect, $U_m > U_1$ and $U_m > U_2$ exist in some mixing ratios, as shown in curve a; for synergistic effect, $U_m > U_1 + U_2$, as shown in curve b; for linear relationship, $U_m = U_1 + U_2$, as shown in curve c; for negative synergistic effect, $U_m < U_1 + U_2$, as shown in curve d in **Figure 1**.

At first, researchers studied the synergistic effect of SF_6 gas mixture in order to solve the problems of high liquefaction temperature, sensitivity to electric field, and the high price of SF_6 gas [7]. However, with the deepening understanding of SF_6 , scholars have found that SF_6 is a strong greenhouse gas. It is estimated that the global annual production of SF_6 gas is more than 20,000 tons and 80% of SF_6 gas produced globally each year is used in the power industry. Although SF_6 has many advantages, its greenhouse effect on the earth cannot be ignored. The global warming potential (GWP) value of SF_6 gas is 23,900; it means that the emission of 1 kg SF_6 is equivalent to the emission of 23,900 kg of CO_2 . What is more serious is that SF_6 has a very stable chemical property, which is difficult to decompose after it spreads to the outside environment, and can exist for up to 3200 years. The environmental impact and greenhouse effect generated by SF_6 will continue to accumulate [8–10].

Affected by climate change, more and more international cooperation has been carried out to reduce greenhouse gas emissions, so as to curb global climate change and maintain the sustainable development of the environment. In the Kyoto protocol of the United Nations framework convention on climate change signed in Kyoto, Japan, in 1997, SF_6 has been clearly regulated as one of the six greenhouse gases and requires developed countries to freeze and reduce the total greenhouse gas emissions [11]. It means that the use of SF_6 in the industrial field will be increasingly restricted and pressured. Therefore, it is an urgent task to study a new gas insulation scheme to replace SF_6 .

Although at present there have been many studies about alternative SF_6 gas, no gas can thoroughly replace SF_6 gas in the form of a single gas; they all have to be mixed with buffer gas for industrial application. The reasonable use of synergistic effect can effectively improve dielectric strength of gas mixtures and reduce the use of insulation gas, so in this paper, the research progress and methods of synergistic effect with gas mixtures are introduced; the prospect and the difficulties in the field were also discussed. This paper is expected to provide help and reference for future research on synergistic effect.

2. Synergistic effect in SF₆ gas mixtures

In view of the synergistic effect and insulation strength of SF₆ mixture, scholars studied and analyzed it through theoretical calculation and experimental research. **Figure 2a** is a simple and intuitive calculation method proposed by Wieland et al. for the insulation strength of SF₆ gas mixture, and **Figure 2b** is the comparison of the calculation results with the actual values and weighted values [12].

Christophorou et al. thought that the preferred gas mixture should include effective electron-attaching gas and/or electron-slowing down gas [13]. The attachment cross section of electron-attaching components should be as wide as possible, or the attachment cross section of different gases is in different energy interval, so the attachment cross section of gas mixtures is also wide. The effect of electron-slowing down gas is to slow down the free electrons, making them easier to attach and reducing secondary ionization. Based on this theory, they believed that when an electronegative gas and a gas with a large dipole moment are mixed, the synergistic effect and insulation strength of the gas mixture will be better. **Figure 3** shows the experimental results of SF₆ gas mixtures with CF₄, CHF₃, and 1,1,1-CH₃CF₃ gas, and the electric dipole moments of these three gases are 0, 1.65D, and 2.32D, respectively.

From the figure, it can be seen that the breakdown voltage curve of SF₆-CF₄ gas mixtures shows almost a linear trend, and the electric dipole moments of CF₄ is 0. When it comes to SF₆-CHF₃ gas mixture, as the content of SF₆ gas increases, the breakdown voltage of the gas mixtures does not increase in a straight line, and there is synergistic effect that occurs. The electric dipole moments of 1,1,1-CH₃CF₃ gas is 2.32D, which is the one with the largest electric dipole moment among the three gases; from **Figure 3c** it can be seen that the synergistic effect of this gas mixture is the most pronounced.

Okubo et al. investigated the partial discharge (PD) and breakdown characteristics of SF₆-N₂ gas mixtures in order to analyze the relationship between electronegativity, additive gases, and the insulation strength [14]. They believed that the synergistic effect of gas mixture is related to the change of discharge form. **Figure 4** shows the

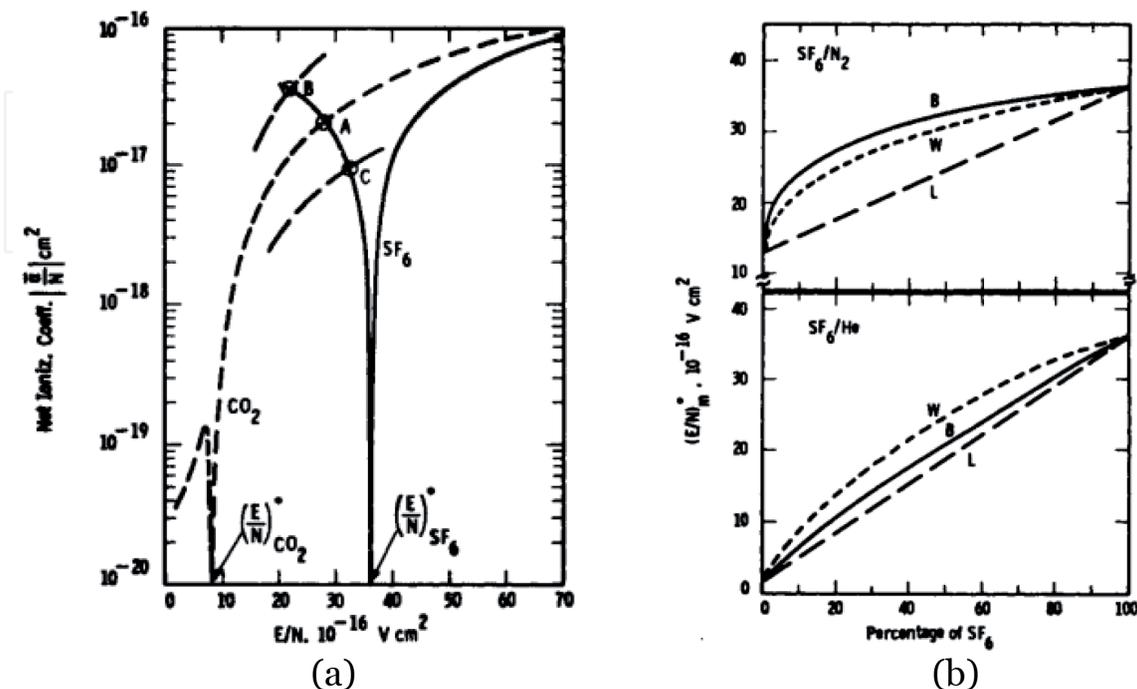


Figure 2. Experimental results of SF₆ gas mixtures. (a) Wieland calculation method, (b) Results comparison of different methods.

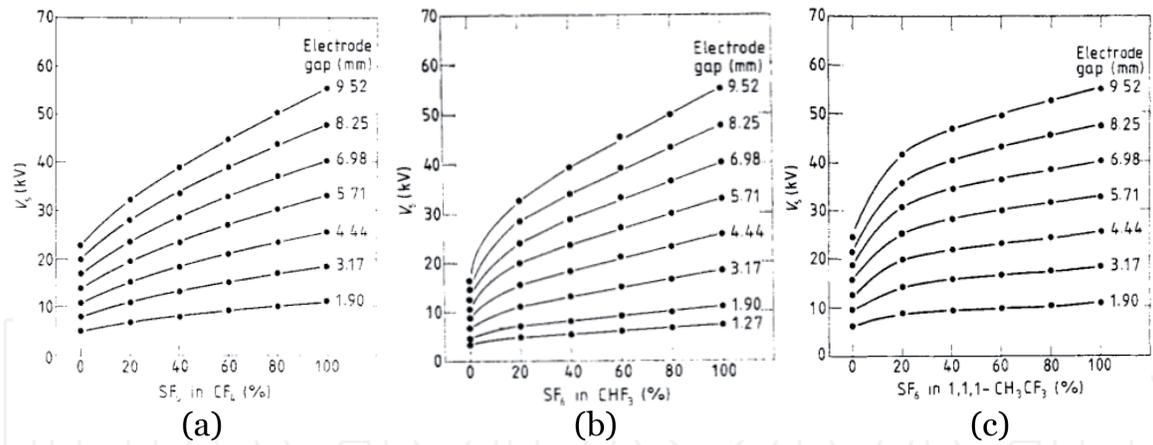


Figure 3. Experimental results of SF₆ gas mixtures. (a) SF₆-CF₄, (b) SF₆-CHF₃, (c) SF₆-1,1,1-CH₃CF₃.

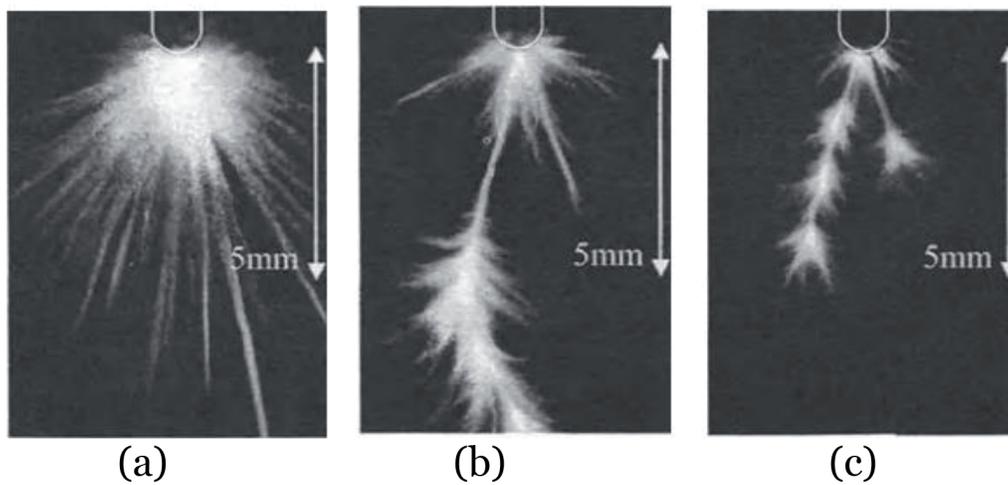


Figure 4. Impulse PD in SF₆-N₂ gas mixture. (a) 0.1MPa, (b) 0.2MPa, (c) 0.3MPa.

impulse PD of SF₆-N₂ gas mixture at different pressure. The needle-plate electrode was used in the experiment, and the content of SF₆ was 10% and N₂ was 90%.

It can be seen that with the change of gas pressure, the development of impulse PD has changed. When the gas pressure is 0.1 MPa, as shown in **Figure 5a**, the brush-like partial discharge occurred around the needle electrode, and it can be thought of as streamer discharge. When the pressure increases to 0.2 MPa, it can be seen from **Figure 5b** that the development of discharge process becomes longer; streamer discharge turns into leader discharge. As the pressure continues to increase, when the pressure is 0.3 MPa, the PD type of the gas mixture is still the leader discharge, and the path of discharge development becomes shorter with the increase of the pressure.

Yamada et al. studied the insulation properties of a kind of gas mixture containing ultra-dilute SF₆ gas [15]. It has been found that trace SF₆ has a significant effect on the streamer discharge of the gas mixture. As the SF₆ content increases, the number of the discharge channels decreased significantly, and the number of channels that can reach the plane electrode also reduced, as shown in **Figure 4**. Except for the effect on discharge characteristics, the results show that the breakdown voltage and the PD voltage of SF₆/N₂ gas mixture have a significant synergistic effect. Yamada T thought that the addition of trace SF₆ inhibits the development of streamer discharge process, which leads to synergistic effect.

Osmokrovic et al. conducted an in-depth study on the synergistic effect of SF₆/N₂ under impulse voltage. The experimental results show that the synergistic

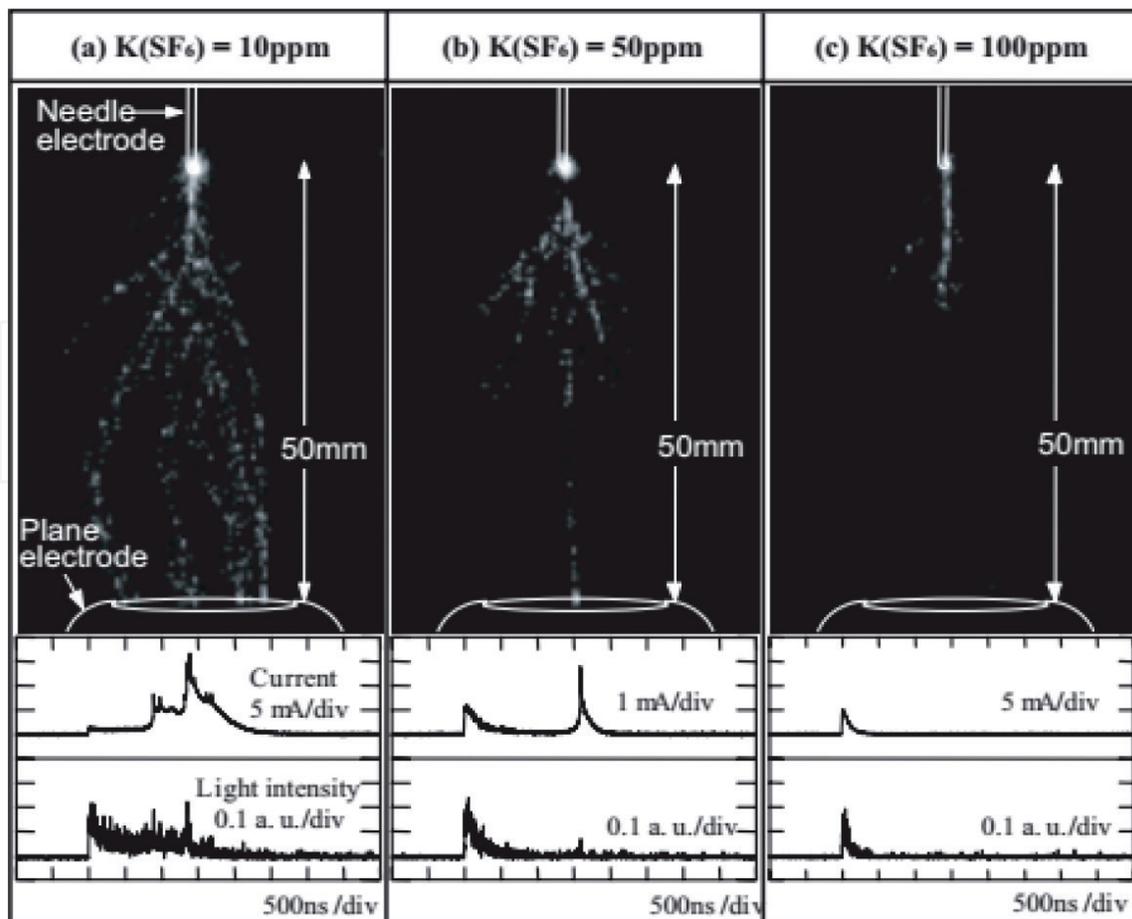


Figure 5.
 PD characteristics in SF₆-N₂ gas mixture.

effect of SF₆/N₂ gas mixture related to the rising rate of the impulse voltage. As the impulse voltage rise rate increases, the synergistic effect is gradually weakened. The synergistic effect of SF₆ gas mixture is very weak and almost completely disappears under some impulse voltage with very high rise rate [16]. The insulation characteristics of SF₆ and SF₆/N₂ gas mixture under impulse voltage with different rise rate are shown in **Figure 5**. The rise rates of shock voltage in **Figure 6a–c** are 1, 50 and 800 kv/ms, respectively.

Based on the above phenomenon, Osmokrovic proposed that after adding N₂ to the SF₆ gas, electrons can make N₂ vibration and rotation dynamics excited or dissociated, this process will make electrons lose energy, and the effective temperature decreases, to realize the modulation of electron energy spectrum and increase the probability that the electrons are captured. The rise rate of impulse voltage has influence on the modulation of the electron energy spectrum, which in turn affects the synergistic effect of SF₆ gas mixture.

Hayakawa et al. studied the generation and development of PD characteristics of SF₆/N₂ gas mixture under positive lightning impulse [17]. PD and breakdown characteristics with different SF₆ content are shown in **Figure 7**. Hayakawa proved through the film of the streak camera and ICCD that the discharge process in SF₆/N₂ gas mixture did change with the increase of gas pressure. Streamer discharge and leader discharge are the two types of PD process in SF₆/N₂ gas mixture, which all have relationship with gas pressure and SF₆ content. With the increase of gas pressure and the content of SF₆ gas, the leader discharge process gradually takes the leading position, and the streamer discharge process of gradually weakens.

Chen studied the discharge characteristics of SF₆/N₂ gas mixture under DC voltage and lightning impulse in extremely uneven electric field. The experimental

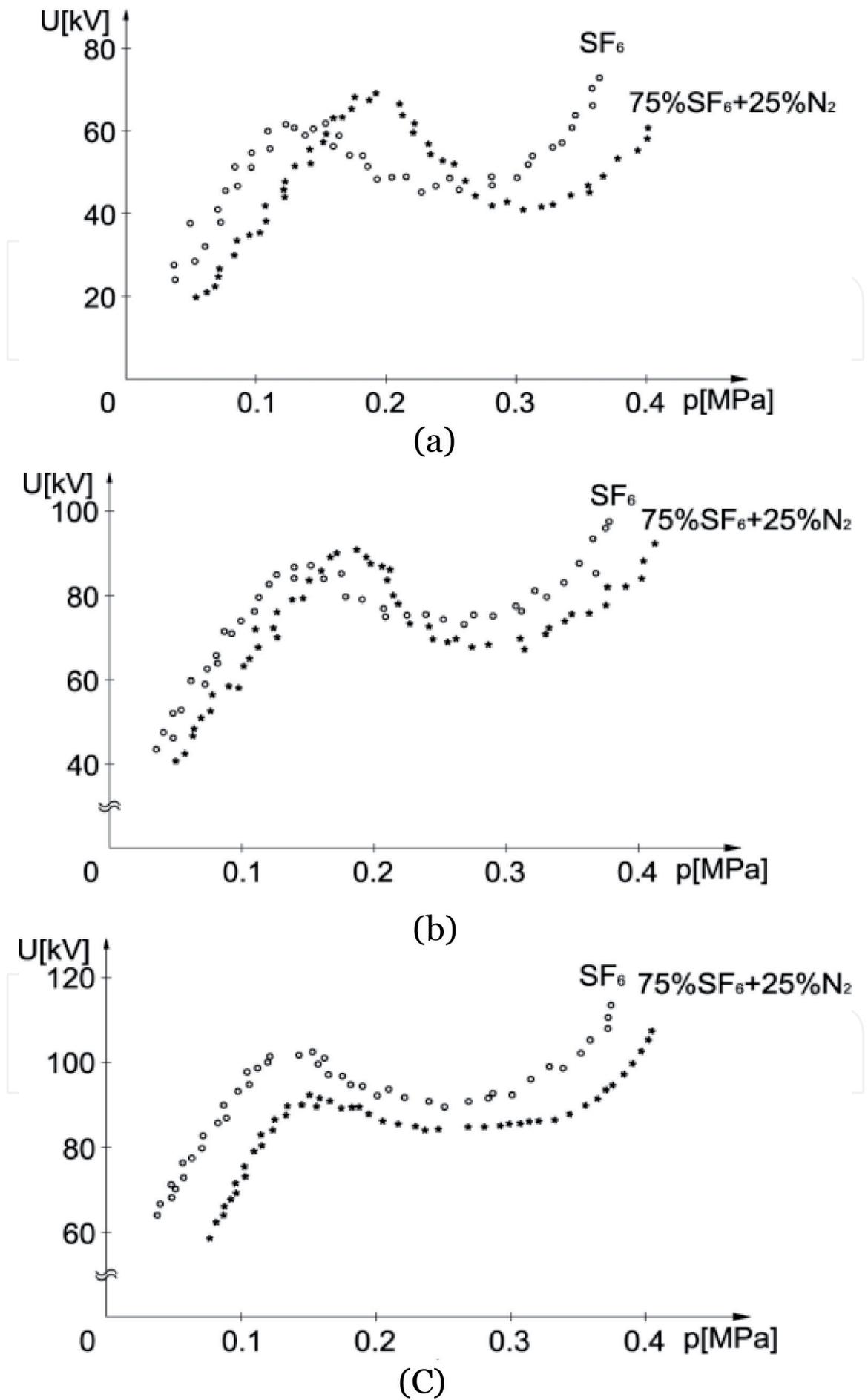


Figure 6. Insulation characteristics of SF₆ and SF₆/N₂ gas mixture under different rising rate impulse voltages. (a) 1kV/ms, (b) 50kV/ms, (c) 800kV/ms.

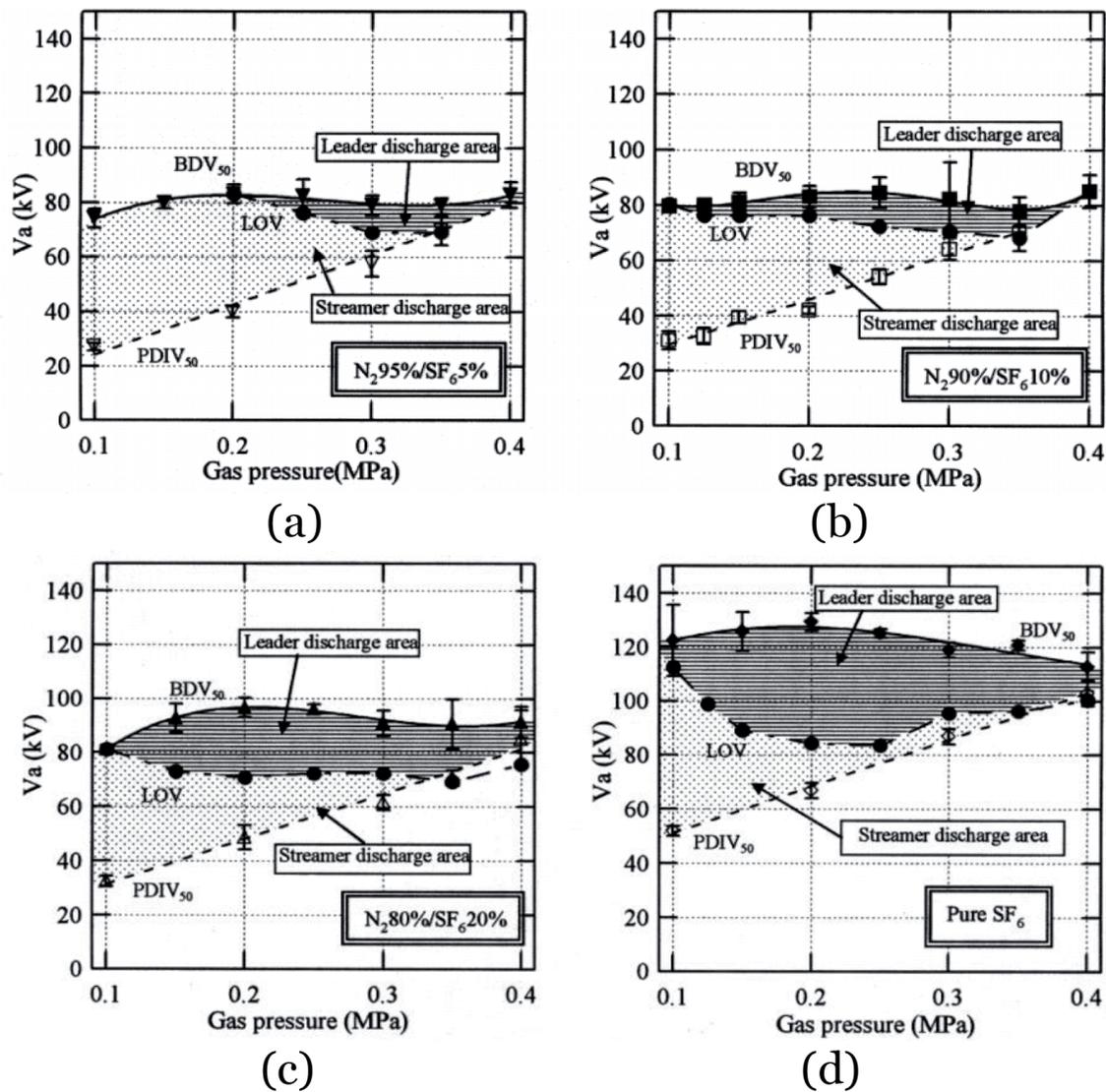


Figure 7. PD and breakdown characteristics with different SF₆ content. (BDV₅₀, breakdown voltage; PDIV₅₀, 50% probability PD inception voltage; LOV, leader discharge onset voltage). (a) SF₆-N₂95%, (b) SF₆10-N₂90%, (c) SF₆20-N₂80%, (d) pure SF₆.

results show that there was a significant decrease of breakdown voltage with the increase of gas pressure under DC voltage and the abnormal discharge characteristics pressure range of SF₆/N₂ gas mixture is larger than SF₆ gas. This phenomenon leads to the breakdown voltage of SF₆/N₂ gas mixture is higher than that of SF₆ gas. So under this abnormal range, positive synergistic effect occurs. However, under lighting impulse voltage, no abnormal discharge phenomenon was found, but positive synergistic effect still existed, as shown in **Figure 8** [18].

Tagashira et al. believe that synergistic effects can be divided into three categories: α -synergistic effect (SF₆ + SiH₄), η -synergistic effect (SF₆ + c-C₄F₈), and γ -synergistic effect (N₂ + CH₄). The research found that the curves of SF₆/SiH₄, SF₆/c-C₄F₈, SF₆/C₃F₆ gas mixtures with SF₆ gas content all decreased first and then increased, that is, the curve had a minimum point. For the curve of SF₆/SiH₄ gas mixture, the falling part of the curve is due to the decrease of ionization coefficient α , that is, α -synergistic effect, and for the curve of SF₆/c-C₄F₈ gas mixture, the rising part is caused by the increase of attachment coefficient η and that is η -synergistic effect. In addition to these two synergistic effects, they also proposed a synergistic effect of γ on the secondary ionization coefficient of N₂ + CH₄ gas mixture [19].

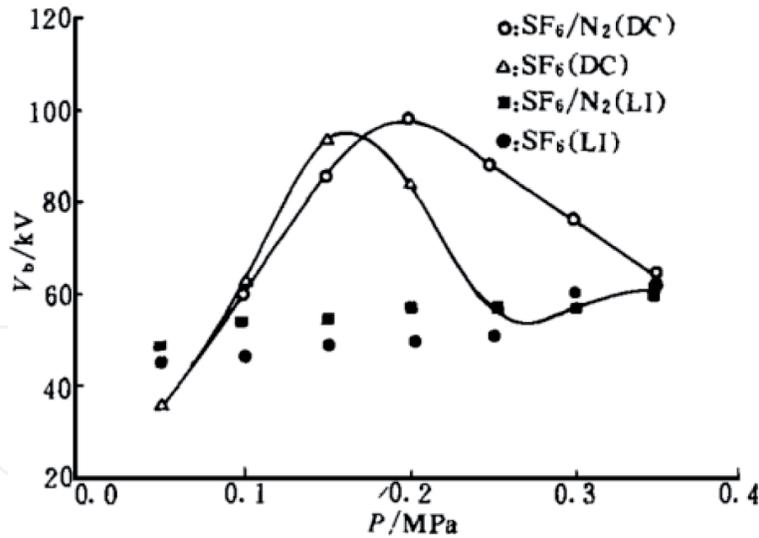


Figure 8.
Abnormal discharge phenomenon in SF₆/N₂ and SF₆.

Takuma et al. studied the synergistic effect of gas mixtures such as SF₆/N₂, CCl₂F₂/N₂, etc. They assumed that the effective ionization coefficient of the gas mixture is equal to the sum of the coefficients of the two component gases multiplied by their respective partial pressure ratios, suggesting an empirical formula for breakdown voltage of SF₆/N₂ gas mixture under slight uneven electric field [20]:

$$U_m = U_2 + \frac{k}{k + C(1 - k)}(U_1 - U_2) \quad (1)$$

where U_1 and U_2 are the breakdown voltage of component gas 1 and gas 2, U_m is the breakdown voltage of gas mixture ($U_1 > U_2$), k is the partial pressure ratio of component gas 1, and C is the synergistic effect coefficient, which is independent of the partial pressure ratio k . When Constant $C = 0.08$, the calculated and experimental values of the SF₆/N₂ gas mixture by this formula are shown in **Figure 5**. The breakdown voltage values are basically the same, which can reflect the synergistic effect of SF₆ gas mixture.

According to formula (1), the formula for calculating the synergy coefficient proposed by Takuma is

$$C = \frac{k(U_1 - U_M)}{(1 - k)(U_M - U_2)} \quad (2)$$

As can be seen from Eq. (2), when $C = 1$, the breakdown voltage of the gas mixture is equal to the weighting value of breakdown voltage of the two components according to the mixing ratio. That is, the breakdown voltage of the gas mixture exhibits a linear relationship that increases as the mixing ratio of the component gas increases. When $0 < C < 1$, the breakdown voltage of the gas mixture reflects synergistic effect phenomenon, and the smaller the value of C , the more significant the nonlinear increase of the breakdown voltage of the gas mixture, which means synergistic effect becomes more significant. When $C = 0$, the breakdown voltage of the gas mixture equals to the breakdown voltage of gas 1, which means $U_M = U_1$.

If all the situations of synergistic effect, i.e., positive synergistic effect, synergistic effect, and negative synergistic, are considered at the same time, then the above formula is no longer applicable. Assuming a positive synergistic effect of the gas mixture, it can be seen from the calculation that the coefficient $C < 0$ under positive synergistic. When the breakdown voltage of the gas mixture is lower than all the breakdown voltage of the component gas, that is, the phenomenon of “super

negative synergistic effect” appears, then value of the coefficient C is still less than 0, so the various synergistic effects of the gas mixture cannot be clearly distinguished by formula (2).

Guo et al. introduced a normalization coefficient h to investigate the synergistic effect of SF₆/N₂ gas mixture under lightning impulse. The definition of coefficient h is as follows:

$$h = \frac{(U_m - U_2) - k(U_1 - U_2)}{0.5(U_1 + U_2)} \quad 0 < k < 1 \quad (3)$$

$$h = 0 \quad k = 0 \text{ or } 1$$

where U_1 , U_2 , U_m , and k in Eq. 3 have the same meaning as those in Eq. 2. When $h > 0$, it means that gas mixture has synergistic effect, and when $h < 0$, it represents that the gas mixture has negative synergistic effect. The relationship between the

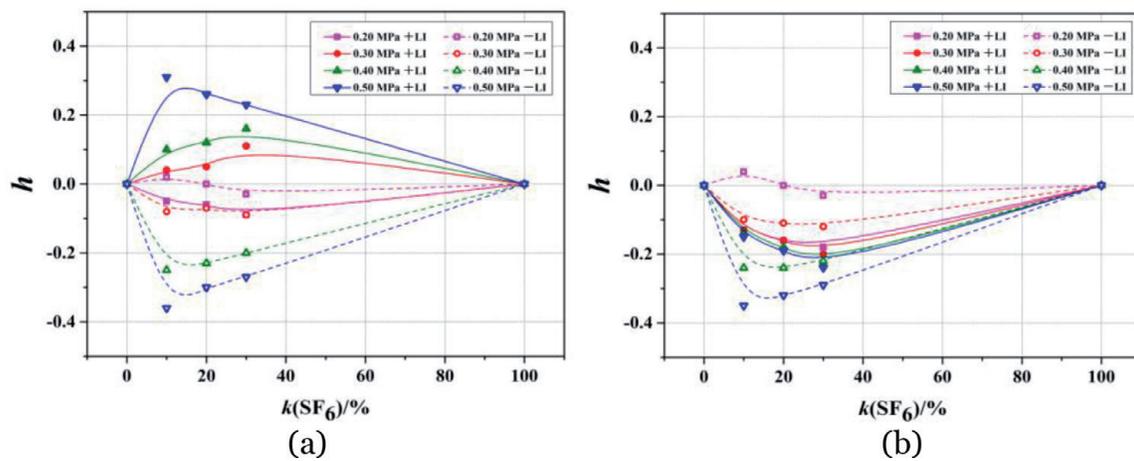


Figure 9. Coefficient h for SF₆/N₂ gas mixture under lightning impulse with different needle-plane electrode (R is radius curvatures of needle electrodes). (a) $R = 2$ mm, (b) $R = 1$ mm.

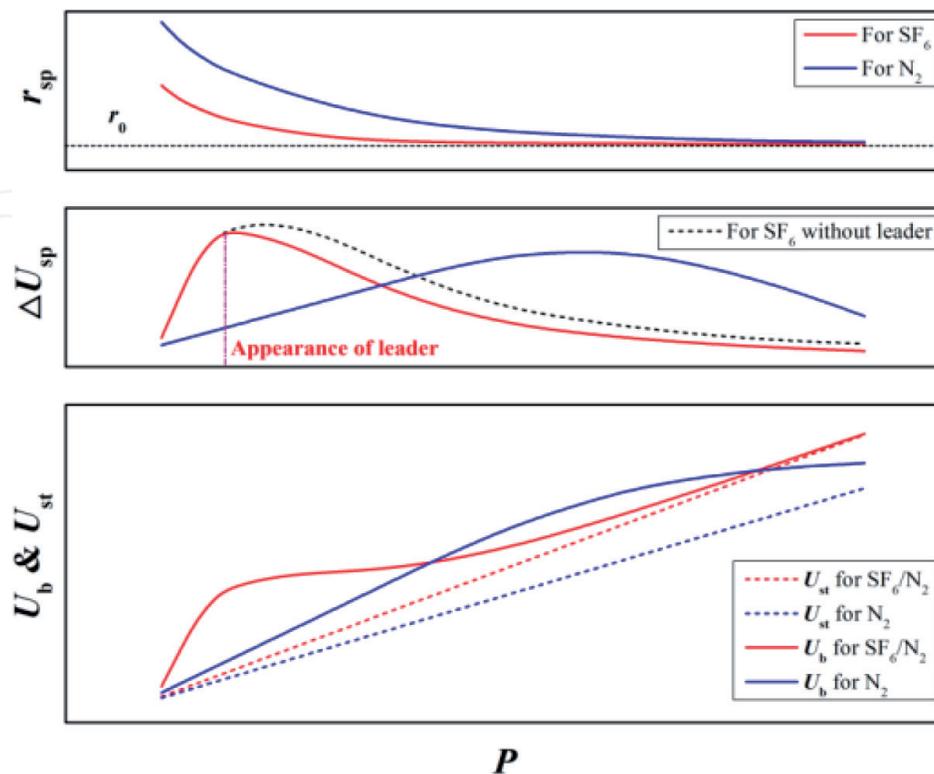


Figure 10. Breakdown voltage differences between N₂ and SF₆/N₂.

coefficient h of SF₆/N₂ and k under lightning impulse with different needle-plane electrodes is shown in **Figure 9** [21].

The analysis results show that under the action of negative lightning impulse voltage, the negative synergistic effect increases with the increase of gas pressure. The synergistic effect under the positive impact voltage decreases with the decrease of gas pressure. With the increase of the electric field inhomogeneity coefficient, the synergistic effect has a negative synergistic effect. The analysis of the development process of the flow discharge shows that there are three reasons for the negative synergistic effect: similar flow corona starting voltage, different space charge effects, and different N₂ and SF₆/N₂ mixed gas discharge forms. The difference of breakdown voltage between N₂ and SF₆/N₂ gas mixture is shown in **Figure 10**. r_{sp} represents the range of space charge, ΔU_{SP} is the influence of space charge on breakdown voltage, U_{st} is the streamer corona onset voltage, and $U_b = U_{st} + \Delta U_{SP}$.

3. Synergistic effect in SF₆ alternative gas mixtures

3.1 c-C₄F₈

c-C₄F₈ is colorless, odorless, nonflammable, and nonexplosive; the GWP of c-C₄F₈ is about 8700, and the molecular structure of c-C₄F₈ is shown in **Figure 11**. The insulation performance of pure c-C₄F₈ gas is better than SF₆, and the gas mixture of c-C₄F₈ gas has similar insulation characteristics to SF₆, which can meet the requirements of practical application. The liquefaction temperature of c-C₄F₈ is about -6°C, higher than that of SF₆, which is -63.8°C [22]. Therefore, c-C₄F₈ can only be mixed with the gas in a certain proportion to reduce the overall liquefaction temperature of the gas mixture for application.

While studying the synergistic effect of SF₆ gas mixture, Christophorou et al. also conducted a comparative study on the synergistic effect of c-C₄F₈ gas mixtures.

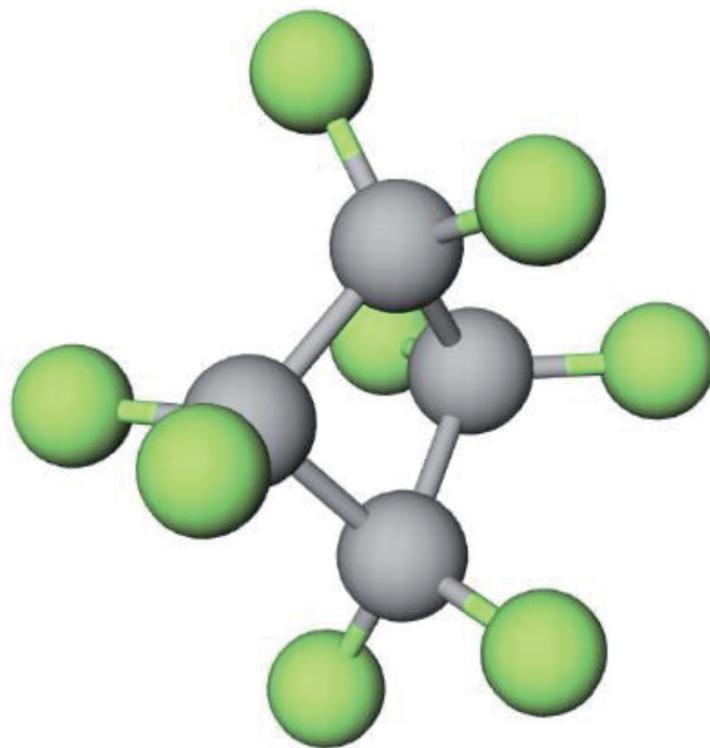


Figure 11.
Molecular structure of c-C₄F₈.

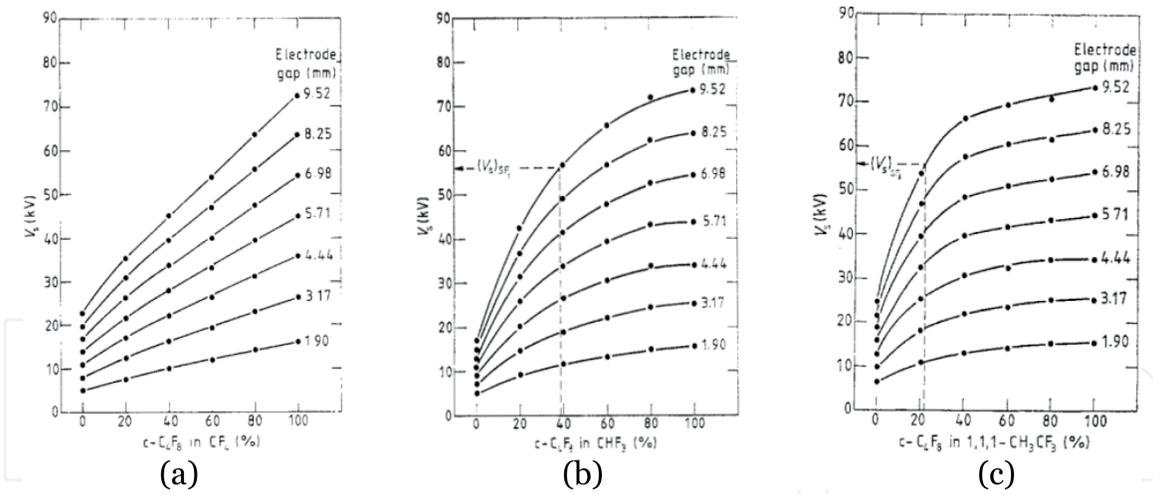


Figure 12. Breakdown voltage of $c\text{-C}_4\text{F}_8$ gas mixtures for various electrode gaps. (a) $c\text{-C}_4\text{F}_8/\text{CF}_4$, (b) $c\text{-C}_4\text{F}_8/\text{CHF}_3$, (c) $c\text{-C}_4\text{F}_8/1,1,1\text{-CH}_3\text{CF}_3$.

The insulation characteristics and synergistic effect of $c\text{-C}_4\text{F}_8/\text{CF}_4$ and $c\text{-C}_4\text{F}_8/\text{CHF}_3$ gas mixture are shown in **Figure 12** [13].

It can be seen from the figure that the addition of a small amount of $c\text{-C}_4\text{F}_8$ can greatly improve the insulation strength of gas mixture. Mixing 20% $c\text{-C}_4\text{F}_8$ in CHF_3 can double the breakdown voltage. The insulation strength of $c\text{-C}_4\text{F}_8/1,1,1\text{-CH}_3\text{CF}_3$ gas with the same mixing ratio is the same as that of pure SF_6 gas. By comparison, it can be seen that the synergistic effect phenomenon will also occur when $c\text{-C}_4\text{F}_8$ gas and the gas with large dipole moment are mixed.

Xing et al. discussed the feasibility of replacing SF_6 gas with $c\text{-C}_4\text{F}_8/\text{N}_2$ mixture for gas insulation equipment from the perspective of PD performance. The initial PD voltage of $c\text{-C}_4\text{F}_8/\text{N}_2$ gas mixture was measured under different pressure, different mixing ratio, and different electrode distance. The influence of these three factors on the PD performance of the gas mixture was obtained and compared with the initial PD voltage of pure SF_6 gas. The results show that the initial PD voltage of pure $c\text{-C}_4\text{F}_8$ gas is 1.3 times that of pure SF_6 gas [23]. $c\text{-C}_4\text{F}_8$ and N_2 have synergistic effect, and the synergistic coefficient calculated by Takuma's equation under different electrode distance and gas pressure is shown in **Table 1**.

Yamamoto et al. examined the insulation characteristics of $c\text{-C}_4\text{F}_8$ gas mixtures such as $c\text{-C}_4\text{F}_8/\text{N}_2$, $c\text{-C}_4\text{F}_8/\text{air}$, and $c\text{-C}_4\text{F}_8/\text{CO}_2$ under different electric field [24]. The experimental results show that $c\text{-C}_4\text{F}_8/\text{CO}_2$ gas mixture has better synergistic effect than the other two mixtures, and improve gas pressure or gap distance can greatly

Electrode distance/mm	Gas pressure/ Mpa	C			
		5% $c\text{-C}_4\text{F}_8$	10% $c\text{-C}_4\text{F}_8$	15% $c\text{-C}_4\text{F}_8$	20% $c\text{-C}_4\text{F}_8$
10	0.20	0.48	0.50	0.54	0.53
	0.25	0.20	0.40	0.44	0.63
20	0.20	0.47	0.86	0.45	0.52
	0.25	0.34	0.50	0.49	0.54
30	0.20	0.15	0.25	0.30	0.36
	0.25	0.24	0.32	0.34	0.41

Table 1. Synergistic coefficient for $c\text{-C}_4\text{F}_8/\text{N}_2$.

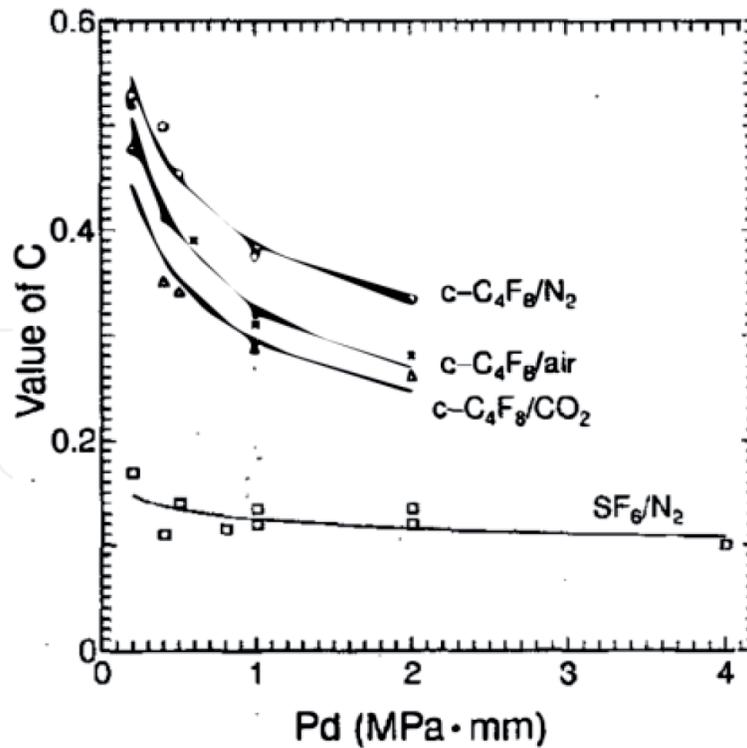


Figure 13.
Relationship of synergistic effect coefficient C with Pd .

enhance the synergistic effect of $c\text{-C}_4\text{F}_8$ gas mixture. The relationship of synergistic effect coefficient C with Pd is shown in **Figure 13**.

3.2 CF₃I

CF₃I gas is odorless, nonflammable, chemically stable, and material compatible. The molecular structure of CF₃I is shown in **Figure 14**. CF₃I is considered as one of the ideal alternatives to conventional Freon refrigerant. In terms of environmental characteristics, CF₃I is an extremely environmental friendly gas, and its GWP value is about 1–5, much lower than SF₆ gas. At the same time, the C-I chemical bond in the molecular structure of CF₃I is easy to photolysis under solar radiation, resulting in the very short existence time of CF₃I in the atmosphere, and the ozone destruction potential of the gas can also be ignored. The boiling point of CF₃I at normal pressure is -22.5°C , which indicates that CF₃I gas will transform from gaseous to liquid when the temperature is lower than -22.5°C [25]. Therefore, CF₃I gas must be mixed with buffer gas before it can be used in power equipment.

Urquijo et al. experimentally measured the electron transport parameters of CF₃I and CF₃I/N₂ gas mixture. They analyzed and studied several parameters including electron drift velocity, diffusion coefficient, electron ionization coefficient, and attachment coefficient by means of pulsed Townsend method. Experimental results show that the critical electric field intensity $(E/N)_{\text{lim}}$ of CF₃I was 437Td, and the insulation strength of the gas is about 1.2 times that of SF₆ gas. When the content of CF₃I is 70%, the dielectric strength of CF₃I/N₂ gas mixture is basically the same with pure SF₆ gas [26]. The insulation characteristic comparison of CF₃I/N₂ and SF₆/N₂ gas mixtures IS shown in **Figure 15**. From the figure it can be seen that CF₃I/N₂ and SF₆/N₂ gas mixture both have synergistic effect phenomenon, but the phenomenon of CF₃I/N₂ gas mixture is weak when compared with SF₆/N₂.

In addition to CF₃I/N₂ mixture, there is also a synergistic effect of CF₃I/CO₂ mixture. Jiao et al. studied the gas mixture of CF₃I/CO₂ with low content of CF₃I,

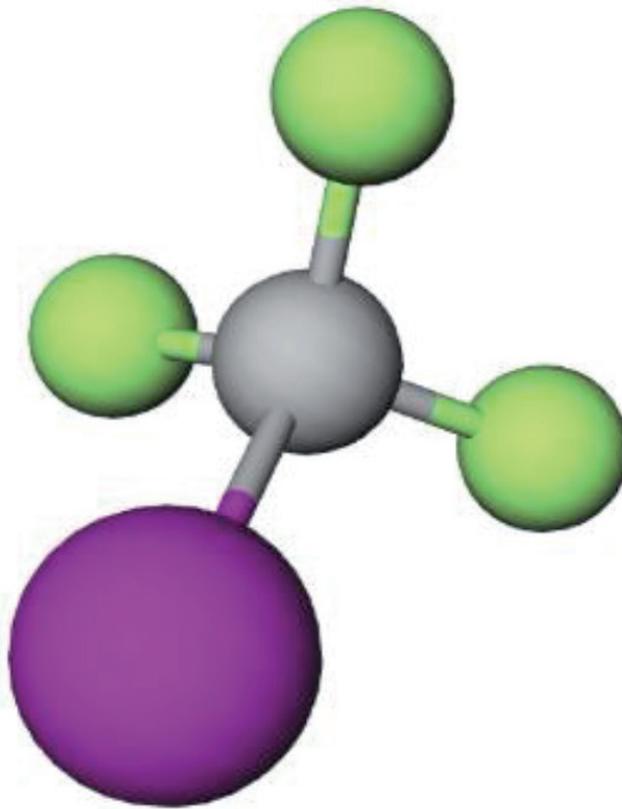


Figure 14.
 Molecular structure of CF_3I .

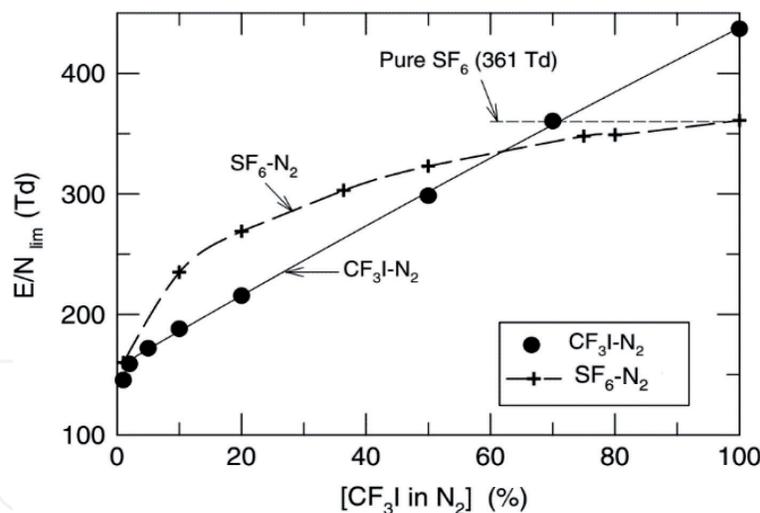


Figure 15.
 Comparison of insulation strength between CF_3I/N_2 and SF_6/N_2 .

and conducted breakdown test on CF_3I/CO_2 gas mixture with different mixing ratio, different gas pressure, and different discharge gap distance under extremely uneven electric field [27]. The experimental results show that the mixing of trace CF_3I can significantly increase the breakdown voltage, and the breakdown voltage tends to be stable when the content of CF_3I gas is over 6%. Although there is still a gap of the breakdown voltage between CF_3I/CO_2 and SF_6 , the trace amount of CF_3I has a good synergistic relationship with CO_2 mixture. The relationship between breakdown voltage and CF_3I content under different electrode distances is shown in **Figure 16**, and the synergistic coefficient of CF_3I/CO_2 gas mixture calculated by Takuma's equation is shown in **Table 2**. The author believes that the negative synergistic effect coefficient is caused by the saturation of the breakdown voltage and

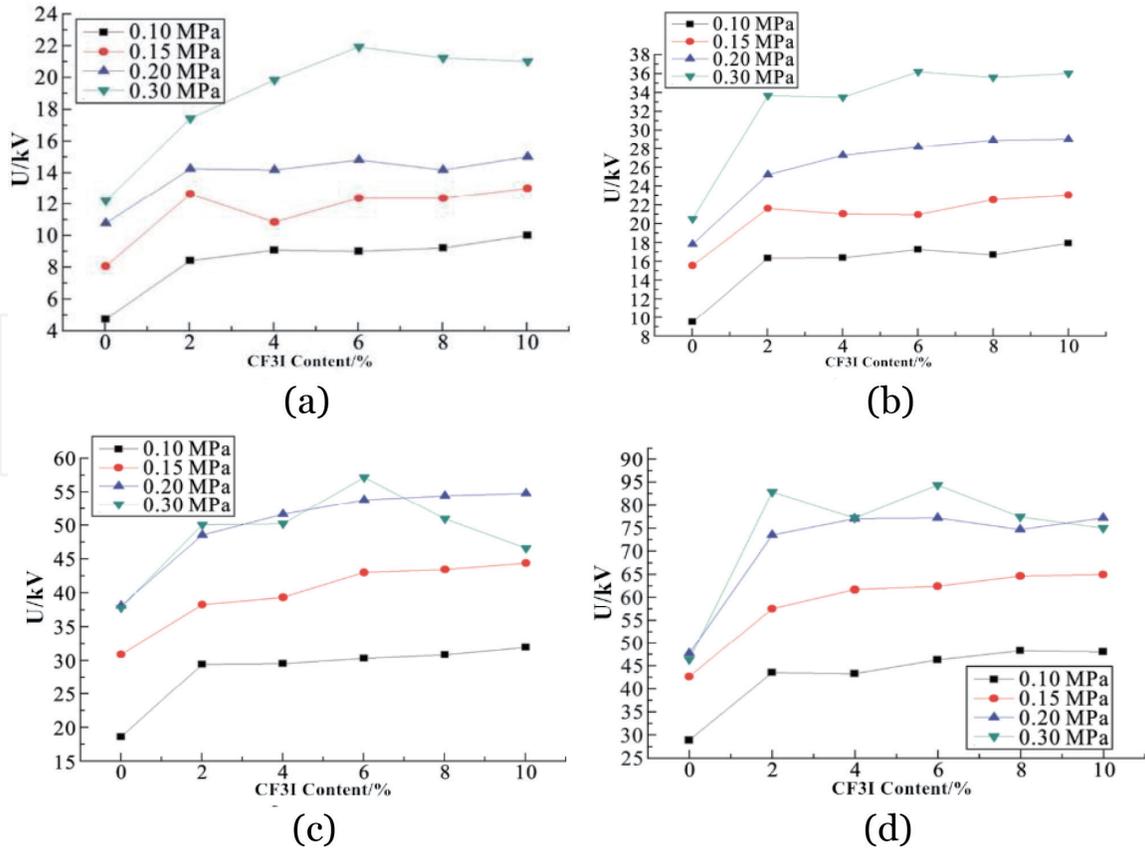


Figure 16. Relationship between breakdown voltage and CF_3I content under different electrode distance. (a) 5 mm, (b) 10 mm, (c) 20 mm, (d) 30 mm.

Gap distance /mm	Pressure /MPa	Synergetic coefficient			
		2% CF_3I	4% CF_3I	6% CF_3I	8% CF_3I
5	0.10	0.11	0.14	0.35	0.72
	0.15	0.02	0.52	0.22	0.60
	0.20	0.06	0.16	0.08	0.99
	0.30	0.17	0.10	-0.14	-0.09
10	0.10	0.06	0.15	0.13	0.68
	0.15	0.06	0.24	0.58	0.27
	0.20	0.13	0.12	0.12	0.04
	0.30	0.05	0.15	0.02	0.20
20	0.10	0.06	0.15	0.22	0.36
	0.15	0.21	0.40	0.18	0.31
	0.20	0.15	0.16	0.10	0.04
	0.30	-0.07	-0.20	-0.82	-1.32
30	0.10	0.08	0.22	0.15	-0.05
	0.15	0.12	0.11	0.19	0.06
	0.20	0.04	0.01	0.01	0.38
	0.30	-0.05	-0.05	-0.37	-0.32

Table 2. Synergetic coefficients of CF_3I/CO_2 gas mixtures using Takuma's equation.

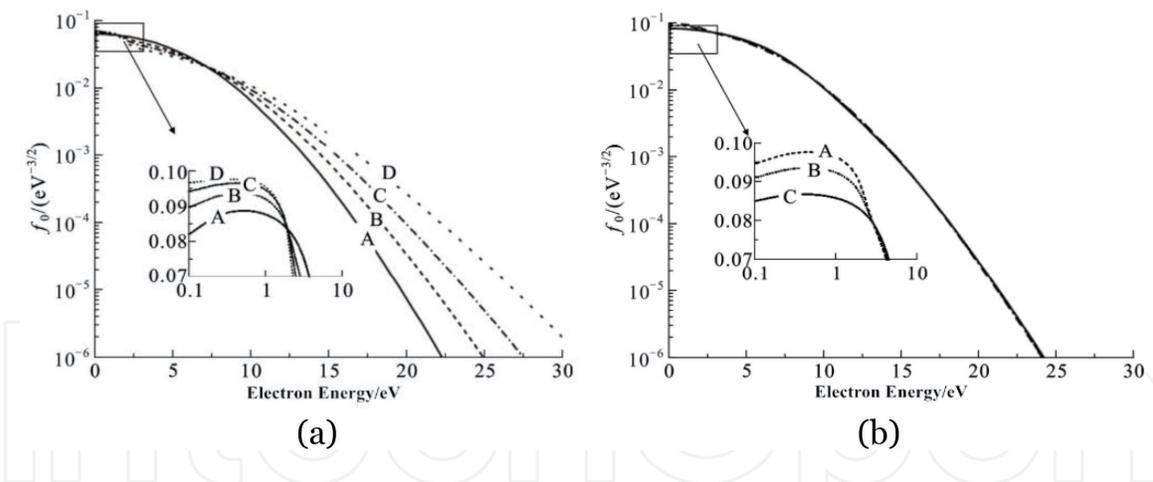


Figure 17. EEDF of CF_3I ternary gas mixtures. (a) $CF_3I/SF_6/N_2$, (b) $CF_3I/N_2/CF_4$.

does not continue to analyze the reason. In fact, this phenomenon may be related to the abnormal breakdown of the gas mixture containing CO_2 .

In addition to binary CF_3I gas mixture, some scholars have studied ternary gas mixture containing CF_3I gas. Xu et al. calculated the electron energy distribution function (EEDF) of CF_3I ternary gas mixtures by solving the Boltzmann equation and propose a new equation to analyze synergistic effect. The results show that if buffer gases such as N_2 or CO_2 are concluded in the ternary mixture, the distribution of low-energy electrons in EEDF increases, leading to the synergistic effect, but there is no synergistic effect with CF_4 . The mixture of two strongly electronegative gases, CF_3I/SF_6 , shows weak negative synergistic effect, while the addition of N_2 or CO_2 can reduce the negative synergistic effect [28]. The EEDF of CF_3I ternary gas mixtures is shown in **Figure 17**.

The computational formula of synergistic effect coefficient proposed by Xu is as follows:

$$\xi = \frac{(E/N)_{\text{lim,mix}}}{\sum x_i (E/N)_{\text{lim,i}}} - 1 \quad (4)$$

where $(E/N)_{\text{lim,mix}}$ is the critical reduced field intensity of gas mixture and $(E/N)_{\text{lim,i}}$ is the critical reduced field intensity of single gas. x_i is the molar fraction of the gas component. Fix the buffer mole fraction of gas to 0, 10, and 30%, and change the mixing ratio of CF_3I and SF_6 gas; the $(E/N)_{\text{lim}}$ and synergistic effect coefficient of CF_3I ternary gas mixtures are shown in **Figure 18**.

3.3 C_4F_7N

C_4F_7N is an SF_6 alternative gas jointly developed by Alstom of France and 3 M of the United States. The commodity name of this gas is Novec 4710, which is an organic compound containing four C atoms and seven F atoms. Its molecular structure is shown in **Figure 19**. The chemical characteristics of the gas are similar to those of fluoro organic gas, and the chemical characteristics are relatively stable, which can achieve good compatibility with other materials in electrical equipment. The relative molecular weight of C_4F_7N is 195.0, and it also has a high liquefaction temperature, which is $-4.7^\circ C$ [29]. Therefore, it also needs to be mixed with buffer gas.

C_4F_7N gas mixture is a popular alternative to SF_6 . At present, most researches on SF_6 alternative gases are concentrated on this gas. In order to obtain the optimal buffer gas type and mixing ratio in C_4F_7N gas mixture, Hu et al. studied the power frequency breakdown performance and synergistic characteristics of C_4F_7N/CO_2 and C_4F_7N/N_2 gas mixture with uniform electric field [30]. The gas pressure is

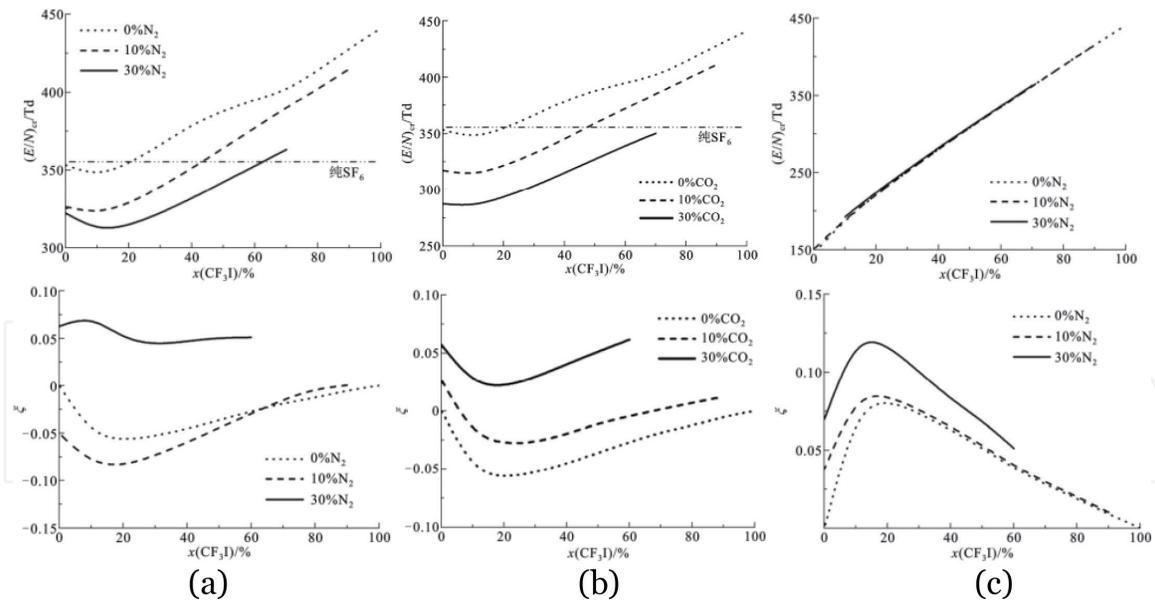


Figure 18. The $(E/N)_{lim}$ and synergistic coefficient of CF_3I gas mixtures. (a) $CF_3I/SF_6/N_2$, (b) $CF_3I/SF_6/CO_2$, (c) $CF_3I/CF_4/N_2$.

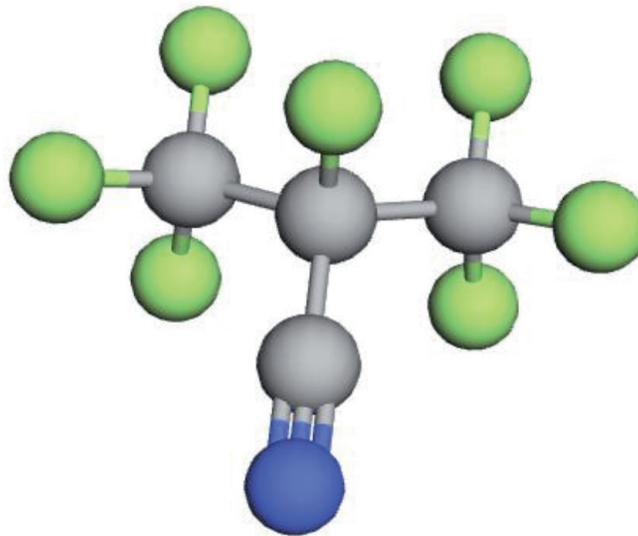


Figure 19. Molecular structure of C_4F_7N .

0.1–0.7 MPa, and the C_4F_7N content ratio in gas mixture is 5–20%. The experimental and calculation results show that the C_4F_7N/CO_2 and C_4F_7N/N_2 gas mixture both have synergistic effects, and the synergistic effect of C_4F_7N/CO_2 is stronger than C_4F_7N/N_2 . The interaction between C_4F_7N and CO_2 bimolecular is stronger than that of C_4F_7N and N_2 , and the research indicates that there is a certain correlation between the synergistic effect of C_4F_7N gas mixture and the intermolecular interaction. This result presents the theoretical calculation and analysis direction for the qualitative judgment of the synergistic effect of C_4F_7N gas mixture. The synergistic coefficient h of C_4F_7N/CO_2 and C_4F_7N/N_2 calculated by Guo Can's equation is shown in **Table 3**.

Zheng et al. also studied the synergistic effect and insulation performance of C_4F_7N/CO_2 gas mixture and found that the synergistic coefficient was related to avalanche parameters of pure gas. They proposed a graphical method based on the Wieland approximation to calculate the critical electric field of gas mixture.

Gas type	Pressure /MPa	Coefficient h			
		5% C ₄ F ₇ N	7% C ₄ F ₇ N	9% C ₄ F ₇ N	13% C ₄ F ₇ N
C ₄ F ₇ N/CO ₂	0.1	0.57	0.63	0.69	0.77
	0.2	0.49	0.59	0.63	0.69
	0.3	0.46	0.52	0.57	0.69
	0.4	0.45	0.53	0.57	0.69
	0.5	0.45	0.54	0.59	0.73
	0.6	0.47	0.55	0.62	0.75
	0.7	0.50	0.58	0.64	0.76
C ₄ F ₇ N/N ₂	0.1	0.40	0.46	0.53	0.62
	0.2	0.44	0.51	0.57	0.63
	0.3	0.34	0.41	0.48	0.56
	0.4	0.35	0.42	0.48	0.56
	0.5	0.37	0.43	0.48	0.56
	0.6	0.39	0.46	0.50	0.64
	0.7	0.44	0.52	0.58	0.64

Table 3.
 Synergistic coefficient h of C₄F₇N/CO₂ and C₄F₇N/N₂ gas mixture.

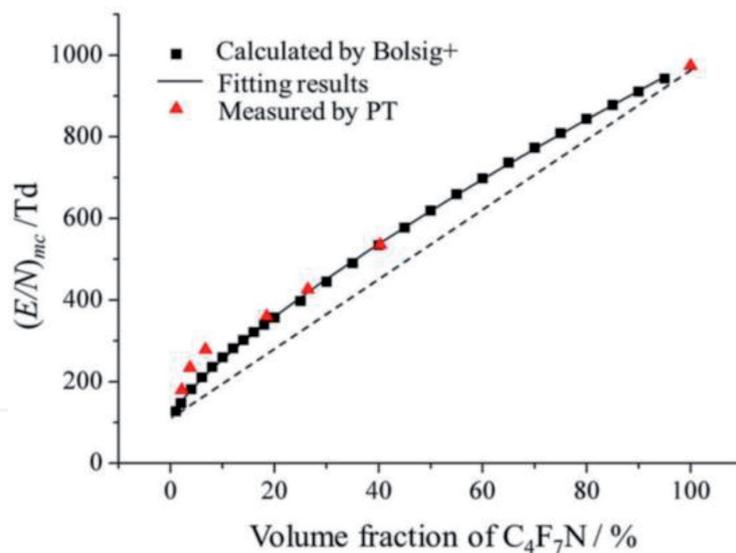


Figure 20.
 The relationship of the critical electric field of gas mixture and C₄F₇N content.

Based on the formula, the C₄F₇N content takes 9% in gas mixture tends to be the optimal mixing ratio [31]. **Figure 20** shows the relationship of the critical electric field of gas mixture and C₄F₇N content.

4. Conclusions

With the development of the power system, gas-insulated equipment such as GIS will be more and more widely used. At present, SF₆ gas is still the most used insulating gas in power systems. However, due to the greenhouse effect of SF₆ gas and the

consensus of countries on the development of low-carbon clean energy systems, it is imperative to use new environmental friendly insulating gas in power equipment. Looking for SF₆ replacement gas will also be a continuing research hotspot in the field of electrical engineering. According to the current research status, the replacement of SF₆ by single gas and its application in gas insulation equipment is still in the laboratory research stage. The use of an electronegative gas mixed with a buffer gas is a well-feasible solution. This paper reviews the research status of the synergistic effect of insulating gas mixtures including SF₆ gas. It has been found that some achievements have been made in the process and mechanism of synergistic effect, the types of synergistic effects under different conditions, and their influencing factors:

1. SF₆, c-C₄F₈, CF₃I, and C₄F₇N gas all have synergistic effects when mixed with various buffer gases. SF₆/N₂ gas mixture will have negative synergistic effect under the lightning impulse. The synergistic effect of the gas mixture composed of c-C₄F₈, CF₃I and C₄F₇N and CO₂ is more significant than that after mixing with N₂.
2. The synergistic effect of gas mixture is affected by the type of gas and external conditions such as gas pressure, electric field type, voltage type, etc. The synergistic effect of the same gas mixture may change with the change of external conditions, such as from synergistic effect to negative synergistic or from negative synergistic to synergistic effect.
3. The synergistic effect of the gas mixture has a certain relationship with the electronic transport parameters. However, since the assumptions of the parameter calculation differ greatly from the external conditions of the experimental measurements, the interpretation of the synergistic effect is not universal.
4. The synergistic effect of gas mixture has a relationship with the discharge pattern. When synergistic effect occurs, the initial discharge voltage of the streamer discharge rises. When negative synergistic phenomenon occurs, the streamer discharge gradually changes to leader discharge, and the discharge starting voltage decreases.

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Author details

Su Zhao and Dengming Xiao*
Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai,
China

*Address all correspondence to: dmxiao@sjtu.edu.cn

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References

- [1] Koch H, Hopkins M. Overview of gas insulated lines (GIL). In: IEEE Power Engineering Society General Meeting. 2005. pp. 940-944
- [2] Yunkun D. Basic Research of the Environmentally Friendly Insulating Gas CF_3I for its Application in Electric Power Apparatus [PhD Thesis]. Shanghai: Shanghai Jiao Tong University; 2016
- [3] Hertz W, Motschmann H, Wittel H. Investigations of the properties of SF_6 as an arc quenching medium. Proceedings of the IEEE. 1971;**59**(4):485-492
- [4] Malik NH, Qureshi AH, Theophilus GD, et al. Prebreakdown phenomenon in SF_6-N_2 mixtures at various pressures. Electrical insulation. In: 1978 IEEE International Conference on Electrical Insulation. 1978. pp. 140-145
- [5] Abdelsalam M, Abdellah M. Dielectric strength of compressed insulating gases and their mixtures. IEEE Transactions on Industry Applications. 1978;**IA-14**(6):516-522
- [6] Wootton RE, Chantry PJ. A critique of methods for calculating the dielectric strength of gas mixtures and a proposed test for, η -synergism. In: Proceedings of the Second International Symposium on Gaseous Dielectrics. Knoxville, USA; 1980. pp. 32-42
- [7] Kline LE, Davies D, Chen C, et al. Dielectric properties for SF_6 and SF_6 mixtures predicted from basic data. Journal of Applied Physics. 1979;**50**(11):6789-6796
- [8] Zhao S, Xiao D, Xue P, et al. Analysis of insulation performance and polar effect of CF_3I/CO_2 mixtures. IEEE Transactions on Dielectrics and Electrical Insulation. 2018;**25**(4):1364-1370
- [9] Ravishankara AR, Solomon S, Turnipseed AA, et al. Atmospheric lifetimes of long-lived halogenated species. Science. 1993;**259**(5092):194-199
- [10] Rinsland CP, Brown LR, Farmer CB. Infrared spectroscopic detection of sulfur-hexafluoride (SF_6) in the lower stratosphere and upper troposphere. Journal of Geophysical Research: Atmospheres. 1990;**95**(D5):5577-5585
- [11] Reilly J, Prinn R, Harnisch J, et al. Multi-gas assessment of the Kyoto protocol. Nature. 1999;**401**(6753):549
- [12] Chantry PJ, Wootton RE. A critique of methods for calculating the dielectric strength of gas mixtures. Journal of Applied Physics. 1981;**52**(4):2731-2739
- [13] Christophorou LG, James DR, Mathis RA. Dielectric gas mixtures with polar components. Journal of Physics D: Applied Physics. 1981;**14**(4):675
- [14] Okubo H, Hayakawa N. Dielectric characteristics and electrical insulation design techniques of gases and gas mixtures as alternatives to SF_6 . In: Gaseous Dielectrics X. Springer; 2004. pp. 243-252
- [15] Yamada T, Ishida T, Hayakawa N, et al. Partial discharge and breakdown mechanisms in ultra-dilute SF_6 and PFC gases with N_2 gas. Journal of Physics D: Applied Physics. 2002;**35**(21):2760-2765
- [16] Osmokrovic P, Stojkanovic M, Stankovic K, et al. Synergistic effect of SF_6 and N_2 gas mixtures on the dynamics of electrical breakdown. IEEE Transactions on Dielectrics and Electrical Insulation. 2012;**19**(2):677-688
- [17] Hayakawa N, Yoshitake Y, Koshino N, et al. Impulse partial discharge characteristics and their mechanisms under non-uniform

- electric field in N_2/SF_6 gas mixtures. IEEE Transactions on Dielectrics and Electrical Insulation. 2005;**12**(5):1035-1042
- [18] Chen Q, Xiao D, Qiu Y. Discharge characteristics of SF_6/N_2 gas mixture. Journal of Xi'an Jiaotong University. 2001;**35**(4):338-342
- [19] Nakanishi K. New gaseous insulation. IEEE Transactions on Electrical Insulation. 1986;**EI-21**(6): 933-937
- [20] Takuma T, Watanabe T, Kita K. Breakdown characteristics of compressed-gas mixtures in nearly uniform fields. Proceedings of the Institution of Electrical Engineers. 1972;**119**(7):927-928
- [21] Guo C, Zhang Q, Ma J, et al. Negative synergistic effect of SF_6/N_2 gas mixtures in non-uniform electric field under lightning impulse. IEEE Transactions on Dielectrics and Electrical Insulation. 2018;**25**(4):1393-1402
- [22] Zhao S, Jiao J, Zhao X, et al. Synergistic effect of c- C_4F_8/N_2 gas mixtures in slightly non-uniform electric field under lightning impulse. In: IEEE Electrical Insulation Conference. IEEE; 2016. pp. 531-534
- [23] Xing W, Zhang G, Li K, et al. Experimental study of partial discharge characteristics of C_4F_8/N_2 mixtures. Proceeding of the CSEE. 2011;**31**(7):119-124
- [24] Yamamoto O, Takuma T, Hamada H, et al. Applying a gas mixture containing c- C_4F_8 as an insulation medium. IEEE Transactions on Dielectrics and Electrical Insulation. 2001;**8**(6):1075-1081
- [25] Zhao S, Xiao D, Xue P, et al. Experimental research on polarity effect of CF_3I/N_2 mixtures under lightning impulse. IEEE Transactions on Dielectrics and Electrical Insulation. 2018;**25**(4):1357-1362
- [26] De Urquijo J, Juárez AM, Basurto E, et al. Electron impact ionization and attachment, drift velocities and longitudinal diffusion in CF_3I and CF_3I-N_2 mixtures. Journal of Physics D: Applied Physics. 2007;**40**(7):2205
- [27] Jiao J, Xiao D, Zhao S, et al. Insulation characteristics for CF_3I-CO_2 gas mixtures with low proportion of CF_3I in extreme non-uniform electric field. High Voltage Engineering. 2017;**43**(3):772-779
- [28] Xu L, Cheng L, Du W, et al. Analysis of the insulation characteristic of CF_3I ternary gas mixture using Boltzmann equation. High Voltage Engineering. 2017;**43**(3):721-726
- [29] Li Y, Zhang X, Xiao S, et al. Decomposition properties of C_4F_7N/N_2 gas mixture: An environmentally friendly gas to replace SF_6 . Industrial & Engineering Chemistry Research. 2018;**57**(14):5173-5182
- [30] Hu S, Zhou W, Zheng Y, et al. Power Frequency Breakdown Experiments and Synergistic Effect Analysis of C_4F_7N/CO_2 and C_4F_7N/N_2 Mixtures. High Voltage Engineering. In press
- [31] Zheng Y, Yan X, Chen W, et al. Calculation of electrical insulation of C_4F_7N/CO_2 mixed gas by avalanche characteristics of pure gas. Plasma Research Express. 2019:025013