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Surface Flashover Characteristics of Epoxy Resin Composites in SF_6/CF_4 Gas Mixture with DC Voltage

Xin Wang [1], Zhimin Wang [1], Jieyuan Chen [1], Xiaofei Shi [2] and Xiaolong Li [3,*]

1 State Grid Jilin Electric Power Company Research Institute, Changchun 130021, China; xinwang_jlepri@163.com (X.W.); zhiminwang_jlepri@163.com (Z.W.); sutguangkuozhang@163.com (J.C.)
2 State Grid Jilin Electric Power Company, Changchun 130022, China; sut_sswang@163.com
3 School of Electrical Engineering, Shenyang University of Technology, Shenyang 110870, China
* Correspondence: xiaolongli@sut.edu.cn

Abstract: SF_6/CF_4 mixture is considered a potential substitution for SF_6 in gas-insulated equipment owing to the considerable insulation and low temperature characteristics of CF_4. This paper concerns the substitutability of the mixture on the surface flashover property. Epoxy resin composites for solid insulators are applied since flashover at the insulator interface often occurs and results in severe damage to the safe operation of the equipment. Two kinds of electrode systems are designed to study DC flashover properties with different electric field uniformities. The obtained result shows that the flashover voltage in the 20% SF_6/80% CF_4 mixture achieved more than 70% of the voltage in SF_6 at the same pressure. The mixture shows considerable synergy in the surface flashover process and performed different tendencies with varying gas pressures and contents under different electrode systems due to the influence of surface accumulated charge. Moreover, it is considered that surface charge due to ionization may result in a reversal phenomenon for voltage polarity with increasing pressure. The results indicate the possibility of SF_6/CF_4 functioning as an efficient substitution of SF_6 with a considerable insulation property and improved environmental protection characteristics.

Keywords: gas-insulated switchgear; SF_6/CF_4 mixture; surface flashover; surface charge; synergistic effect; epoxy resin; insulator; substitute gas

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1. Introduction

SF_6 is widely applied in gas-insulated switchgear (GIS) due to its excellent insulation and arc-quenching properties [1,2]. However, SF_6 was classified as a limited gas in the Kyoto Protocol due to the serious greenhouse effect and durable activity in the atmosphere attributed to its chemical stability [3]. Moreover, the application of SF_6 in GIS is limited in areas with a low temperature due to its high liquefaction temperature [4]. Thus, substitute gas is an urgent need considering the development of power systems and the increasing push for environmental protection to satisfy the demand in low temperatures and environmental applications.

Currently, much concern is focused on the investigation of SF_6 substitute gases for environmental consideration. Two main approaches are present, i.e., the development of gas mixtures based on SF_6 with the application of air, N_2, CO_2, etc. for partial substitution and the development of new gases with an environmental property for perfect substitution [5,6]. c-C_4F_8 and CF_3I were reported with considerable insulation and arc-quenching properties in the investigation of environmental gases [7,8]. However, the high liquefaction temperature of these gases remained a disadvantage, resulting in the limitation for cold applications. It was reported that CF_4 showed favorable properties in cold weather due to its low liquefaction temperature, which could improve the application of SF_6 in cold conditions with the proper amount of the mixture [9]. Moreover, CF_4 demonstrates better environmental properties with a low Global Warming Potential compared to SF_6, which could improve the environmental property of the SF_6/CF_4 mixture compared to SF_6 [10].

Meanwhile, the SF_6/CF_4 mixture presents the advantage of insulation in a non-uniform electric field due to the considerable insulation property of CF_4 and showed a proper synergistic effect [11,12]. Furthermore, the 50% SF_6/50% CF_4 mixture was applied in the high voltage breaker owing to its excellent arc-quenching property [13,14]. However, the research on the SF_6/CF_4 mixture has mainly focused on its insulation and arc properties as a SF_6 substitute gas for the purpose of application in high voltage (HV) breakers in GIS.

With the development of high-voltage direct-current (HVDC) transmission, surface flashover would cause a severe challenge to the insulator in GIS owing to the accumulation of surface charge under the stress of the DC field [15–17]. However, research concerned with DC flashover has mostly focused on SF_6 [18], and little attention has been paid to the gas mixture or new environmental gas. Meanwhile, the studies on gas mixture are mainly concerned with the insulation and arc properties. Few researchers have discussed the influence of the SF_6/CF_4 mixture on the surface property of insulators, especially for HVDC. This paper investigated the DC surface flashover property of epoxy resin (EP) composites applied in insulators with SF_6/CF_4 mixture. Two kinds of electrode systems with different electric field uniformities were designed to study the influence of the gas property on flashover behavior. Moreover, the influence of stressed voltage polarity was investigated with various SF_6/CF_4 mixtures considering the effect of accumulated surface charge. The synergistic effect was applied to describe the interaction between the two kinds of insulation gas for surface flashover. Finally, the substitutability of SF_6/CF_4 was discussed, with a comprehensive consideration of flashover and environmental properties for GIS.

2. Experimental Setup and Procedure

2.1. Test Sample and Gas Mixture

The EP composites applied in this paper consist of bisphenol-A epoxy resins as the matrix, were filled with Al_2O_3 particles of 70 wt%, and were supplied by Pinggao Group Co., Ltd. (Pingdingshan, China) This composition is often applied in the manufacture of GIS/GIL insulators. Thus, it was selected for this study. The thickness of the samples was 1 mm. The average surface roughness of the samples was 0.12 µm. In this test, CF_4 gas with various contents was mixed in the SF_6 matrix to obtain SF_6/CF_4 mixture with the contents of 20, 40, 60, and 80% for SF_6. According to Dalton's law of partial pressure, the content of gas constituents can be described by the partial pressure in the mixture. In the gas mixture process, a gas constituent with lower content was inflated into a high-pressure gasholder to reduce its compressibility in the following process. Thus, the SF_6/CF_4 mixture was standing for hours before being inflated to the test seal chamber.

2.2. Electrode System

Two kinds of electrode systems were applied in this paper, which could supply electric fields with different uniformities. The surface flashover characteristics of EP samples was investigated with different kinds of electric fields. The electrode systems are illustrated in Figure 1. Two copper finger-type electrodes of the same size were applied as HV and ground electrodes, respectively, whose surfaces were polished. The radius of the tip touching the sample was 8 mm, and the distance of the tip was 5 mm, as shown in Figure 1a. The point electrode was made of tungsten steel with a radius of 1.6 mm and fixed at an angle of 45° to the test sample. The tip was polished and set 5 mm apart from the ground electrode, which was made of copper, as shown in Figure 1b. The inhomogeneous degrees of the electric field in the finger-type electrode system and needle-plate electrode system are 1.7 and 5.2, respectively. Thus, the finger-type electrode system can be employed to investigate the flashover characteristics in a slightly uneven electric field corresponding to the condition of a GIS busbar with a coaxial cylindrical structure. The finger-type electrode system can be employed to investigate the flashover characteristics in an extremely uneven electric field corresponding to the condition of the crack or metallic particle on the insulator surface.

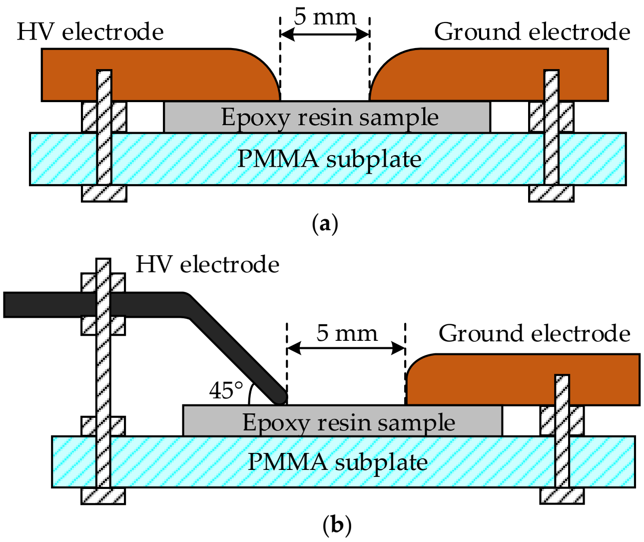

Figure 1. Structure of electrode systems. (**a**) Finger-type electrode system. (**b**) Needle-plate electrode system.

2.3. Surface Flashover Measurement

The flashover measurement system is shown in Figure 2. DC voltage up to 150 kV with positive and negative polarities was provided by an HVDC source. A self-designed seal chamber consisting of viewing windows was applied in the test, which could provide a gas environment with a pressure up to 0.6 MPa. A 126 kV basin insulator supplied by Pinggao Group Co., Ltd. was fixed on the chamber to prevent possible flashover between the HV input electrode and grounding tank.

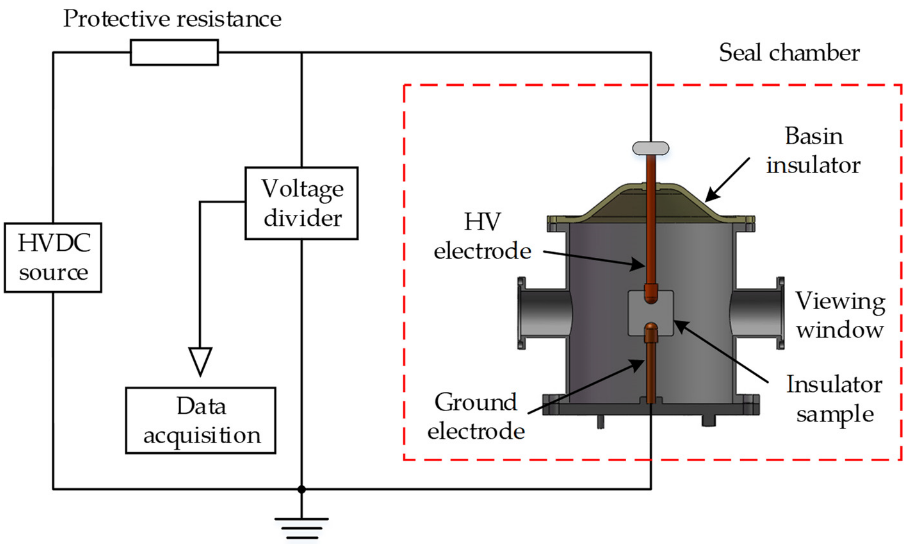

Figure 2. Experimental setups for the surface flashover test.

The EP sample and electrodes were cleaned with ethyl alcohol and dried before being fixed in the chamber to prevent the influence of surface pollution. The seal chamber was vacuumed to 30 Pa, and then SF_6/CF_4 mixture was inflated up to the given pressure. The system was standing for 20 min before HVDC voltage was applied to the sample. DC voltage was applied and increased by 1 kV/s until a flashover occurred. Ten repeated tests were carried out for each condition. The gas pressure that operated in the test was from 0.1 to 0.4 MPa, and the temperature was 20 °C.

3. Results and Discussions

3.1. Surface Flashover

The negative surface flashover of the EP samples under finger-type electrodes was investigated with various SF_6/CF_4 mixtures, and the result is shown in Figure 3. Contents of 0, 20, 40, 60, 80, and 100% for SF_6 were applied in the mixture, and the pressure was operated from 0.1 to 0.4 MPa. It is obvious that, with the increasing pressure, the negative flashover voltage decreased, while the absolute value increased, indicating an increase in the difficulty of the flashover process. Moreover, no significantly saturate tendency appeared within the increase. According to impact ionization theory, the free path of an electron decreases with increasing pressure, leading to the increasing possibility of collision. However, the obtained energy for an electron in the stress of the electric field decreases owing to the decrease of the free path. The two opposite effects result in the decline of the impact ionization coefficient within the given pressure, which contributes to the increasing tendency with increasing pressure.

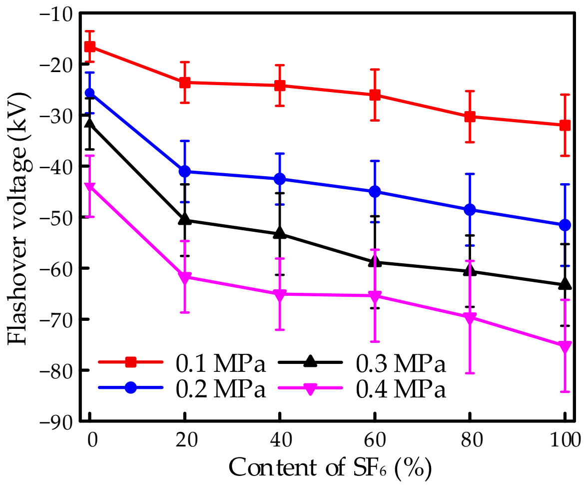

Figure 3. Relation between the flashover voltage and the content of SF_6 with various pressures under the finger-type electrode system.

The flashover strength showed obvious improvement due to the mixture of SF_6, even at low contents compared to CF_4. The flashover voltage achieved increments of 42, 60, 59.4, and 38.2%, respectively, from 0.1 to 0.4 MPa for the 20% SF_6/80% CF_4 mixture compared to CF_4. The electronegativity of the gases for the constituent element of F could result in the adsorption of electrons, thus leading to the generation of negative ions. The influence on impact ionization finally leads to the increase in the flashover property. Thus, the flashover characteristics in CF_4 perform a disadvantage to SF_6 for the deficiency in electronegativity.

It is shown that the flashover strength increased with the increasing content of SF_6. The flashover voltage in the SF_6/CF_4 mixture reached over 70% compared to SF_6, with the content of 20% at the same pressure. The value would reach over 80% at a high pressure. The results in Figure 4 present the voltage ratio between the mixture and SF_6 at the same pressure calculated from Figure 3. The results showed a slight improvement with the increase in the content of SF_6, considering the difference between 20% SF_6/80% CF_4 and 60% SF_6/40% CF_4. This indicated that the 20% SF_6/80% CF_4 mixture would achieve good insulation properties in flashover and show an advantage in the environment-friendly application.

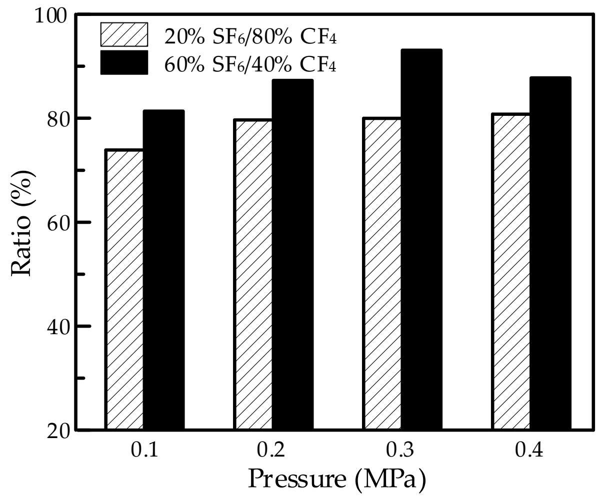

Figure 4. Flashover voltage ratio for various mixtures.

The flashover voltage under the needle-plate electrode system is illustrated in Figure 5. With increasing pressure, the flashover voltage increased, obviously. Similar to the tendency in the finger-type electrode system, the flashover strength achieved a significant improvement with the mixture of SF_6 compared to that of CF_4, which could be attributed to the excellent insulation property of SF_6. Moreover, the flashover voltage increased with the increasing content of SF_6 and performed a saturate tendency. The flashover property performed an obvious increase with the addition of SF_6 at an extremely low content of 20% and then showed a slight improvement with a continuous increase in SF_6. The flashover voltage for the 80% SF_6/20% CF_4 mixture achieved a slight increase compared to the 20% SF_6/80% CF_4 mixture.

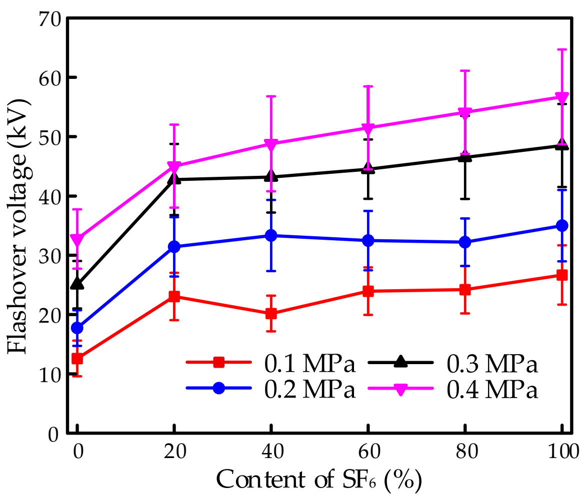

Figure 5. Relation between the flashover voltage and the content of SF_6 with various pressures under the needle-plate electrode system.

Double parameter Weibull distribution fitting was applied to investigate the flashover property with different mixtures. The Weibull fitting can be defined in Equation (1),

$$F(t) = 1 - e^{-(\frac{t}{\eta})\beta}, \quad (1)$$

where the two key parameters mean the shape parameter η and the scale parameter β. F represents the probability of the flashover process. t represents the flashover voltage recorded. The typical results with 100, 80, 60, 40, and 20% SF_6 are shown in Figure 6. The pressure was 0.4 MPa. The shape and scale parameters of the mixture from Weibull fitting are illustrated in Table 1. The shape parameter reflects the slope of probability versus the flashover voltage; a high value indicates a high concentration of voltage. The scale parameter represents the flashover voltage at a probability of 63.2%, calculated from the fitting line as a feature voltage. The fitting results of the flashover property indicated the considerable performance in the 20% SF_6/80% CF_4 mixture compared to SF_6. Moreover, the mixture showed property surface flashover characteristics considering the balance between the shape and scale parameters, along with environmental considerations. The flashover voltage at 63.2% probability in the 20% SF_6/80% CF_4 mixture was calculated as 82.3% of SF_6 with a concentrated disparity.

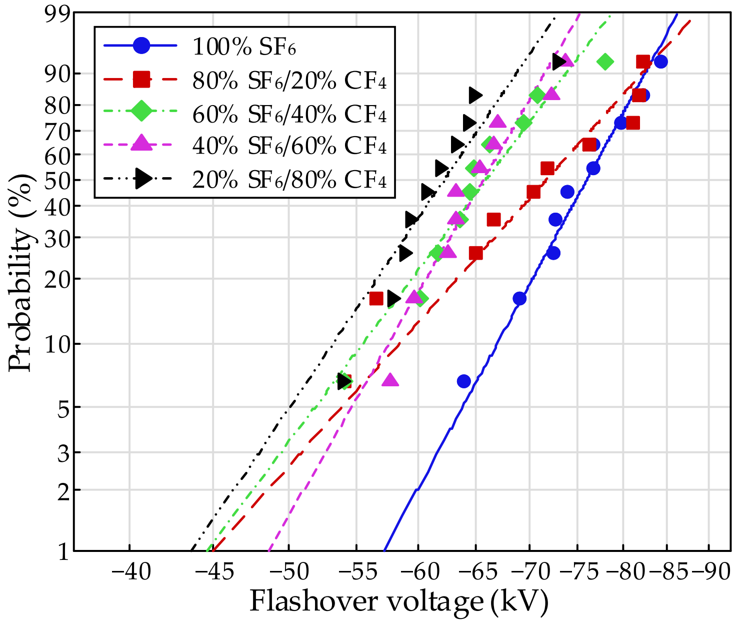

Figure 6. Weibull fitting of flashover voltage with a finger-type electrode system.

Table 1. Shape and scale parameters with a finger-type electrode system.

Gas Mixture	Shape Parameter	Scale Parameter
20% SF_6/80% CF_4	11.98	64.13
40% SF_6/60% CF_4	14.06	67.44
60% SF_6/40% CF_4	10.84	68.23
80% SF_6/20% CF_4	9.04	74.74
100% SF_6	14.89	77.87

The Weibull fitting results of the point-plate electrode system at 0.4 MPa are shown in Figure 7. The voltage distribution with the contents of 20, 40, 60, 80, and 100% for SF_6 was illustrated. The shape and scale parameters calculated are illustrated in Table 2. It was obvious that the flashover voltage increased with the increasing content of SF_6. However, when the content increased from 20 to 80%, the voltage at the probability of 63.2% obtained an increase of only 12.6%. The disparity showed no obvious difference for the various mixtures and displayed concentrate dispersion for the voltage records.

In a real GIS, the gas pressure in the busbar is typically 0.4–0.5 MPa [3]. Thus, the performance of the gas mixture at 0.4 MPa is beneficial in evaluating its substitute for SF_6 gas applied in a real GIS busbar. However, the result indicates the degradation of dielectric strength for the 20% SF_6/80% CF_4 mixture with increasing pressure, especially for pressures higher than 0.3 MPa. It needs to be emphasized that this degradation tendency in Figure 5 is obtained with the needle-plate electrode system, which corresponds to the extremely uneven electric field, while the electric field distribution in the real GIS busbar is slightly uneven. In Figure 3, the result corresponding to a slightly uneven electric field shows a slight degradation tendency for the 20% SF_6/80% CF_4 mixture. Thus, the 20%

SF_6/80% CF_4 mixture can be regarded as a potential substitute for SF_6 gas in cold weather. Attention should be paid to this degradation tendency under extremely uneven electric fields, since local electric field distortion may appear during operation due to the surface defect of the crack or metallic particle.

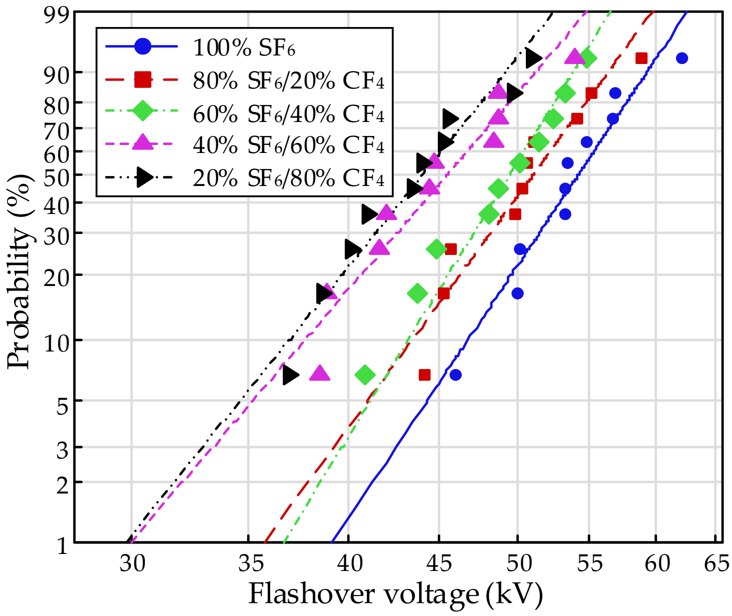

Figure 7. Weibull fitting of flashover voltage with a needle-plate electrode system.

Table 2. Shape and scale parameters with a needle-plate electrode system.

Gas Mixture	Shape Parameter	Scale Parameter
20% SF_6/80% CF_4	10.77	45.56
40% SF_6/60% CF_4	10.11	47.18
60% SF_6/40% CF_4	14.11	50.76
80% SF_6/20% CF_4	11.89	52.61
100% SF_6	13.01	55.71

3.2. Synergistic Effect

The evaluation of the synergistic effect was applied to analyze the influence of the interaction between SF_6 and CF_4 in the flashover process. The synergistic effect concerns the phenomenon that the dielectric strength of the gas mixture shows superiority to the weighted average of each constituent and behaves in a non-linear relation [5,12]. The synergistic effect could be evaluated with Equation (2),

$$U_m = U_2 + \frac{\rho_1(U_1 - U_2)}{\rho_1 + \rho_2 \times C},\ U_1 > U_2, \quad (2)$$

where U_m represents the flashover voltage in the gas mixture consisting of g_1 and g_2. U_1 represents the voltage of g_1, which shows a higher voltage, and U_2 represents the voltage of g_2, with a lower voltage. ρ_1 is the partial pressure ratio of g_1, and ρ_2 is the partial pressure ratio of g_2. C is defined as the synergistic coefficient with a scope from 0 to 1. The voltage increases linearly with the synergistic coefficient equal to 1 while staying the same as a superior gas with the synergistic coefficient equal to 0 when the content of the superior gas was increased. A low coefficient indicates that the same improvement in the insulation property could be achieved with a low content of superior gas. A typical synergistic effect on the performance of the flashover property is shown in Figure 8 with various mixtures. The results illustrated the influence of gas pressure under a finger-type electrode system, with the results of 20% SF_6/80% CF_4, and 40% SF_6/60% CF_4 as examples, calculated from Figure 3.

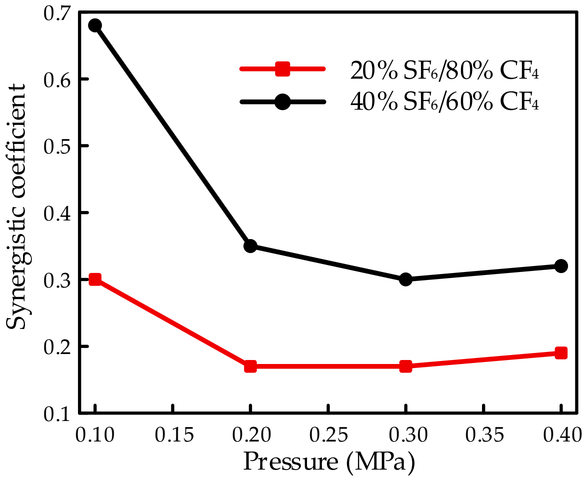

Figure 8. Relation between the synergistic coefficient and pressure with a finger-type electrode system.

The synergistic effect increased as the pressure increased from 0.1 to 0.3 MPa and performed a similar tendency with the breakdown property in the gas mixture. However, by continually increasing the content of SF_6, the synergistic effect decreased slightly, which was opposite to the property in the gas breakdown process.

The synergistic effect under the needle-plate electrode system was illustrated in Figure 9 with the purpose of investigating the influence of pressure on the extreme non-uniform electric field. The synergistic effect decreased with the increasing pressure at high pressures. The non-linear tendency versus pressure is attributable to the influence of accumulated charge on the surface of the EP sample when the sample was applied to the HVDC electric field. Surface charge is considered to accumulate under the stress of the electric field owing to the field emission caused by points on the electrode surface, partial discharge due to the air gap between the solid dielectric and electrode, interlayer polarization considering the difference between dielectrics, discontinuity or non-linearity on the conductivity of the EP sample, etc. [15–17]. Moreover, the accumulation of surface charge would be a serious issue under the HVDC electric field. The accumulated surface charge would lead to a serious distortion of the electric field and promote the flashover process due to the high voltage at high pressures, thus resulting in the decrease in the synergistic effect. Moreover, due to the extreme non-uniform electric field, it would perform more serious charge accumulation, thus leading to a more obvious influence on the synergistic effect, with increasing voltages corresponding to the increasing pressure in the needle-plate electrode system compared to the finger-type electrode. Therefore, the synergistic coefficient in Figure 9 showed a more obvious increasing tendency versus pressure at high pressures from 0.2 to 0.4 MPa. In a previous work, the SF_6/CF_4 mixture showed an excellent synergistic effect in the breakdown characteristics under the extreme non-uniform electric field [11]. However, in flashover characteristics, due to the surface charge accumulation and the corresponding effect of field distortion on the flashover process, the synergistic effect gets worse in the needle-plate electrode system.

The synergistic effect of the finger-type electrode system is shown in Figure 10 with various contents of SF_6. The coefficient increased with the increasing the content of SF_6. This indicates that once a low content of SF_6 was mixed with the CF_4 gas, the mixture would perform a significant improvement in the flashover property. However, by continuously increasing the content of SF_6, the influence of SF_6 would slow down, which confirms the similar tendency with the breakdown characteristics of the gas gap in the SF_6/CF_4 mixture.

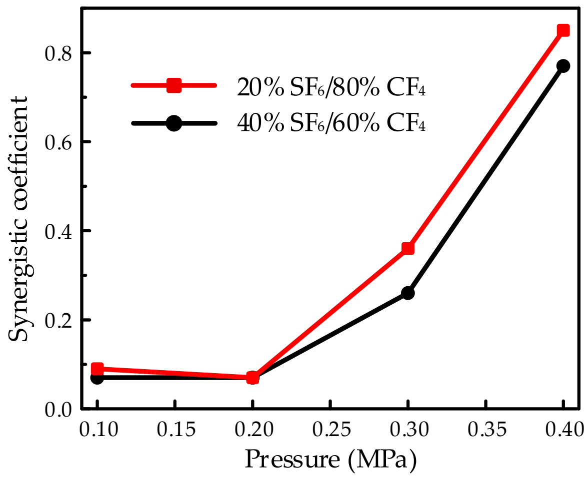

Figure 9. Relation between the synergistic coefficient and pressure with a needle-plate electrode system.

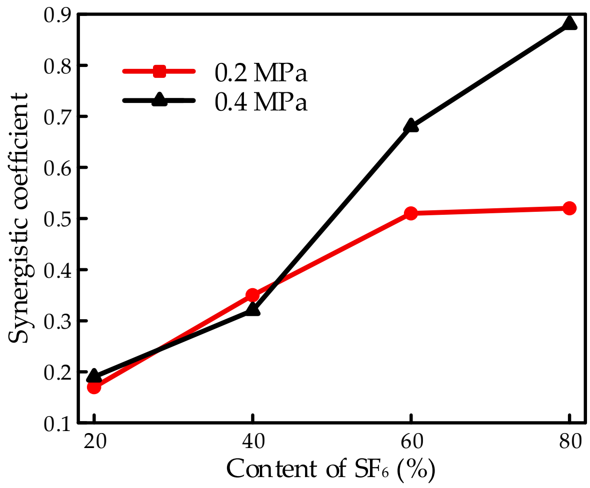

Figure 10. Relation between the synergistic coefficient and the content of SF_6 with a finger-type electrode system.

The synergistic coefficient in the needle-plate electrode system showed a similar monotonic increasing tendency with the increasing content of SF_6 at the pressure of 0.2 MPa, as shown in Figure 11, compared to the result in Figure 10. However, the coefficient showed a non-monotonic increasing tendency with the increasing pressure of the SF_6/CF_4 mixture, as the synergistic coefficient decreased at low contents and grew up, continuously increasing the content. This indicates the influence of non-uniformity on the synergistic effect with the increasing content of SF_6. This may be attributable to the influence of severe discharge in the CF_4 gas and the corresponding accumulation of surface charge. It is considered that discharge and ionization would easily occur in CF_4 gas at low voltages compared to SF_6 due to the disadvantage in the insulation property of CF_4. In this experiment, micro-discharge would occur at an extremely low content of SF_6, especially at high pressures, due to the influence of high voltage before the flashover occurred. This would lead to an increase in the charge accumulation on the dielectric surface and thus promote the possibility of flashover, especially for the extreme non-uniform electric field. With the increasing content of SF_6, the discharge phenomenon was restrained along with the charge accumulation, leading to an increase in the insulation property. Thus, with the increasing content of SF_6 at low contents, the influence of charge accumulation at the interface functions as the key factor due to the excellent insulation property of SF_6 resulting in the suppression of charge accumulation, which leads to an increase in the flashover property.

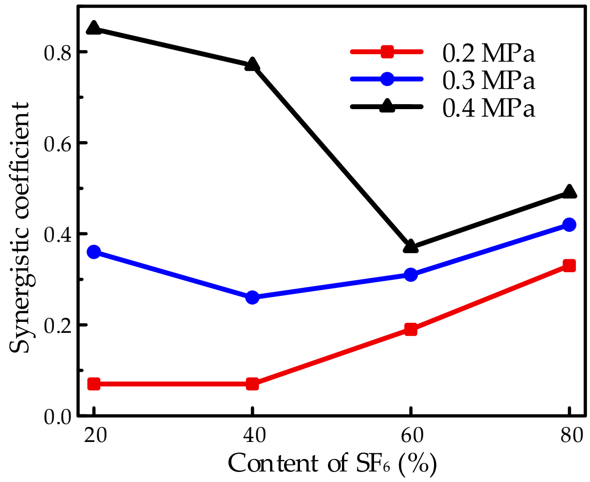

Figure 11. Relation between the synergistic coefficient and the content of SF_6 with a needle-plate electrode system.

3.3. Polarity Property

The flashover property in the mixture at positive and negative polarities was investigated under the needle-plate electrode system with an extreme non-uniform electric field. The typical results with a content of 60% are shown in Figure 12, and the absolute voltage values are illustrated in the figure. As can be seen, the absolute voltage increased with the increasing pressure of the mixture for both the positive and negative polarities. Moreover, when the pressure increased from 0.1 to 0.4 MPa, the negative flashover voltage showed a higher increment compared to the positive polarity. This leads to an obvious reversal of the polarity effect in the flashover property as higher positive flashover voltages occur at lower pressures, while higher negative flashover voltages occur at higher pressures. However, no obvious reversal phenomenon appeared in the test under the finger-type electrode system.

The flashover property for different polarities in the mixture at low pressures is illustrated in Figures 13 and 14. Figure 13 concerns ionization and the charge property and Figure 14 shows the corresponding electric field distribution on the surface due to the charge distribution. Ionization would occur at the tip of the needle electrode and result in the formation of positive ions and electrons. The generated electrons would easily move to the plate electrode with the stress of the external electric field force owing to the low pressure. Thus, the residual, considerable number of positive ions would gather at the solid–gas interface and lead to the accumulation of the surface charge of hetero-polarity with a negative needle electrode, as shown in Figure 13a. This would contribute to the increase in the surface electric field and improve the probability of flashover, as shown in Figure 14a. However, the electrons generated in ionization would move to the needle electrode due to the stress of the electric field force when the needle electrode was applied with positive polarity, as shown in Figure 13b. The residual positive ions would form an accumulated homo-charge at the surface of the EP sample, resulting in the reduction of the electric field strength at the tip. Thus, the flashover process would be restrained due to the accumulated charge. The influence of the accumulated surface charge on the field distribution with a positive needle electrode is shown in Figure 14b.

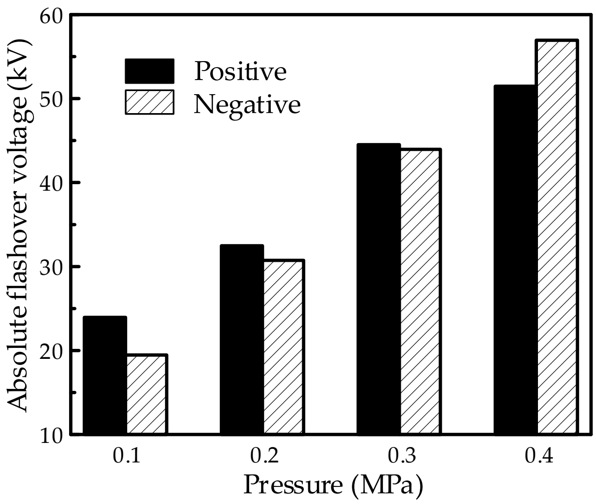

Figure 12. Flashover voltage for needle-plate electrodes under different voltage polarities.

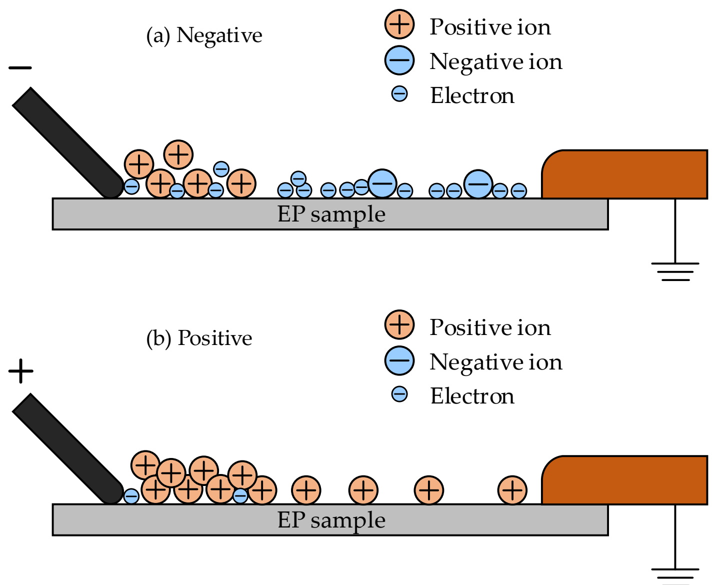

Figure 13. Charge characteristics on the surface at a low pressure with different polarities.

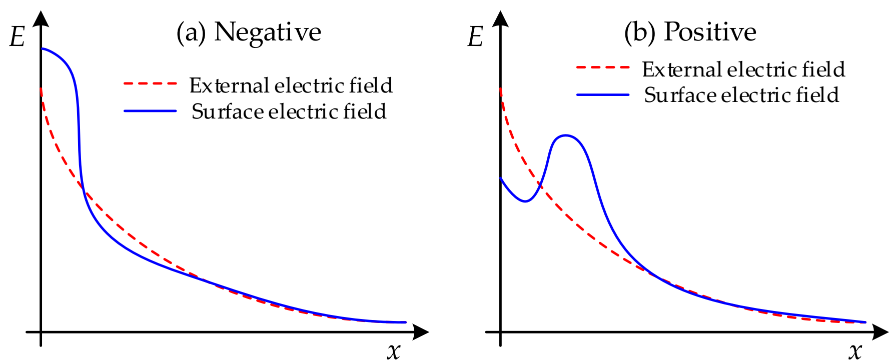

Figure 14. Electric field distribution at a low pressure with different polarities.

Figure 15 illustrated the corresponding influence of the generated ions and the accumulated surface charge when high gas pressure was applied in the flashover process. Meanwhile, the electric field distribution along the surface is shown in Figure 16 considering the influence of accumulated charge. Considering the high pressure applied, it would be restrained for the diffusion and movement of the generated positive ions and electrons, leading to a large amount of charge remaining at the tip area. Due to the high electro-negativity of the SF_6 and CF_4 molecules, the electrons would be attracted, resulting in the formation of numerous negative ions [3,12]. Thus, as illustrated in Figure 15a, these negative ions would accumulate at the surface in the vicinity of the electrode tip as a consequence of the high pressure. This could lead to the decrease in the electric field, as shown in Figure 16a, and contribute to the improvement in the flashover property for the negative needle electrode. However, the accumulated negative surface charge would perform as a hetero-polarity charge, as shown in Figure 15b, with a positive needle electrode at high pressures. Figure 16b illustrates the corresponding enhancement in the electric field strength at the tip. Thus, the voltage showed a low value in positive polarity compared to negative polarity. Due to the strong electronegativity of SF_6, the effect of polarity showed a more serious reversal phenomenon. In this case, the decreasing tendency of the charge property would reduce the reversal property due to the influence of low electronegativity for CF_4. Thus, with the mixture of CF_4, the reversal property would decrease in the mixture.

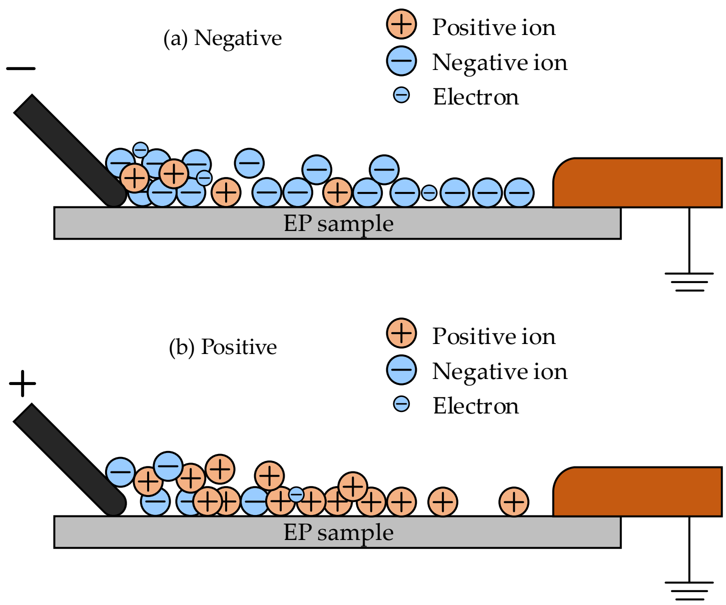

Figure 15. Charge characteristics on the surface at a high pressure with different polarities.

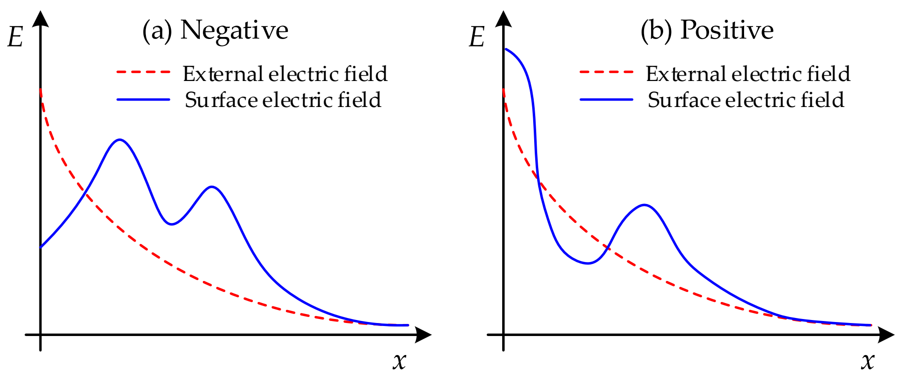

Figure 16. Electric field distribution at a high pressure with different polarities.

It needs to be emphasized that the curves in Figures 14 and 16 are not the exact electric field distribution by the finite element analysis (FEA) calculation, since it is difficult to calculate the surface charge distribution corresponding to the two figures with the FEA method due to the complex reactions and processes in ionization. The curves just illustrate the relative relation between the surface electric field distribution and the external electric field distribution in each condition.

Moreover, due to the enhancement in the uniformity of the electric field, the charge accumulation was prevented, and the influence of surface charge on the polarity property decreased in the finger-type electrode system, as indicated in Figure 17. Thus, the voltage polarity showed no obvious influence on the reversal phenomenon.

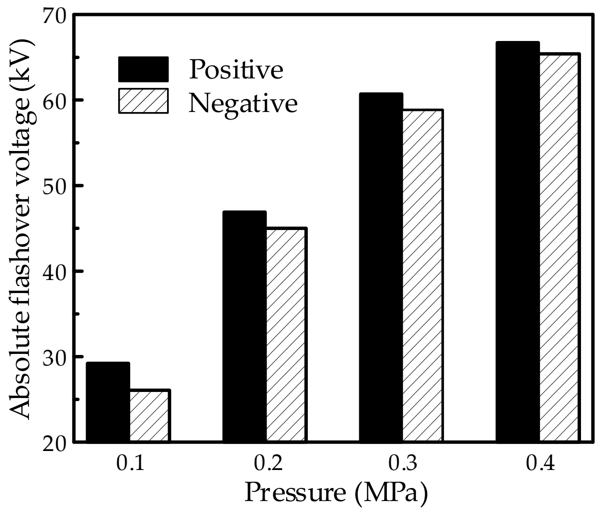

Figure 17. Flashover voltage for finger-type electrodes under different voltage polarities.

It is known that the regenerative dielectric character of SF_6 contributes to its application in circuit breakers as the arc-extinguishing medium. Once referring to the breakdown or flashover performance, the regenerative dielectric character is not that important. The energy released due to flashover is extremely lower than that due to arcing; thus, there is no massive ionization or decomposition of the insulating gas molecule due to flashover compared to what happens during arcing. The ionization or decomposition along the discharge path would be compensated quickly after the flashover owing to the thermal motion of the gas molecule. In the future, the authors will carry out experiments to further reveal the regenerative dielectric character of the SF_6/CF_4 mixture to achieve comprehensive knowledge of the flashover characteristics.

4. Conclusions

The surface flashover on the solid–gas interface is a vital concern in GIS. This paper suggested the SF_6/CF_4 mixture as the alternation for SF_6 with a satisfied insulation property on the flashover behavior for the EP composites. The results can be concluded as follows:

(1) The addition of SF_6 could significantly improve the flashover property of the EP sample in CF_4. The EP composites showed proper characteristics in the SF_6/CF_4 mixture compared to SF_6. The flashover voltage in 20% SF_6/80% CF_4 could reach over 70% of the value in SF_6, and the voltage increased with the increasing content of SF_6.

(2) The synergistic effect increased with the increasing pressure in low pressures and decreased in high pressures, which showed a more obvious tendency in the needle-plate electrode system owing to the influence of surface charge on the flashover process. Moreover, due to the suppression of discharge, the synergistic effect raised with the increasing content of SF_6, while it decreased with the continuously increasing content, especially in an extreme non-uniform electric field.

(3) The flashover voltage showed an obvious reversal tendency with the increasing pressure, especially when the content of SF_6 increased. By increasing the pressure, the formation of negative ions due to the absorption of the ionized electron by SF_6 and CF_4 would reduce the electric field at the tip of the needle electrode as a consequence

of the surface charge. Thus, the negative flashover voltage showed a high value compared to the positive flashover in high pressures, especially with high contents of SF_6, owing to the strong electronegativity which would absorb the ionized electron.

(4) The flashover results of the EP composites indicated the possibility of SF_6/CF_4 functioning as an efficient substitution of SF_6 with a considerable insulation property and improved environmental protection characteristics.

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