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Pollution Flashover Characteristics of Composite Crossarm Insulator with a Large Diameter

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Abstract: The composite crossarm insulator differs greatly from the suspension insulator in structure and arrangement. This study aims to determine the pollution flashover characteristics of composite crossarm insulators under different voltage grades. Four types of AC composite crossarm insulators with diameters ranging from 100 mm to 450 mm are subjected to artificial pollution test, and then the effects of the surface hydrophobicity state of silicone rubber, core diameter, umbrella structure, arrangement, and insulation distance on the pollution flashover voltage of the composite crossarm insulators are analyzed. Under the pollution grade 0.2/1.0 mg/cm^2 and voltage grade from 66 kV to 1000 kV, if the silicone rubber surface changes from HC5 to HC6, the pollution flashover voltage of the composite crossarm insulator will increase by 13.5% to 21.0% compared with the hydrophilic surface. If the core diameter changes from 100 mm to 300 mm, the pollution flashover voltage gradient decreases with the increase in core diameter; if the core diameter changes from 300 mm to 450 mm, the pollution flashover voltage gradient increases with core diameter. Under the same insulation height and core diameter, the umbrella structure will have a certain impact on pollution flashover voltage by up to 1.7% to 5.4%. Under the horizontal arrangement, the pollution flashover voltage can increase by 10.5% to 12.1% compared with that under the vertical arrangement. Under the hydrophilic surface and weak hydrophobicity state, the pollution flashover voltage has a linear relationship with the insulation distance. The above results can provide a reference for the structural design and optimization of the composite crossarm insulator.

Keywords: composite crossarm; pollution flashover characteristics; core diameter; hydrophobicity; umbrella structure; voltage gradient

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1. Introduction

The composite crossarm insulator features good pollution, lightning, and wind deviation protection effects, and is lightweight and easy to install. In addition, it can save power transmission corridors. When being used for electric transmission lines, they can save project costs, improve operational reliability, and produce numerous economic and social benefits [1,2].

Many countries have studied composite crossarms. Since the 1960s, Japan has studied the use of fiber-reinforced polymers (FRPs) for crossarms of electric transmission lines, which could greatly solve flashover accidents due to wind deviation [3–5]. Multiple companies in the USA used FRPs for practical production. Shakespeare Composite Structures™ was the first to develop electric poles with composite materials. These electric poles were installed in Hawaii, where high salt spray corrosion and hurricanes occur frequently, and had been used there for over 40 years. At present, they still have good service conditions. In addition, many FRP manufacturers, such as Newmark, Strongwell, and Ebert, have developed their own FRP power transmission towers [6–8]. In Europe, the 3D electric field computation of a composite crossarm was carried out, and a trial site has been developed within a substation on the Northeast coast of Scotland for the electrical testing of high voltage composite crossarms [9–11]. Although studies on composite crossarms started late in China, they have developed rapidly. In recent years, many scientific institutions and universities have been devoted to studying composite crossarms. China Electric Power Research Institute developed electrical tests, mechanical tests, and construction technology research for composite crossarms under multiple voltage grades [12,13]. The Northwest Electric Power Design Institute cooperated with Xi'an Jiaotong University to study the electric field distribution, electrical test, and mechanical structure for a 750 kV composite crossarm tower, obtain the interstitial discharge characteristics of tower head and the voltage-resistant characteristics of composite crossarm insulators reflecting pollution conditions in the northwest region and use a 750 kV composite crossarm for the electric transmission line of Hami Nan-Shazhou project [14,15]. Tsinghua University cooperated with China Southern Power Grid to conduct a pollution flashover test for composite crossarms under a 500 kV high altitude and observed arc development [16]. The composite crossarm manufacturers NARI and SHEMAR studied the internal materials of large-size composite outdoor insulators and ensured the internal insulation strength of composite insulators with a large diameter through air inflation and filling in polymer materials [17,18].

In sum, numerous studies have focused mainly on the mechanical performance of composite crossarm structures, the simulation of electric field distribution, the insulating property of materials in crossarm, and the electrical property of a single voltage grade. However, the pollution flashover characteristics of composite crossarm insulators have not been systematically studied. In addition, composite crossarm insulators largely differ from suspension insulators in diameter, arrangement form, and umbrella structure [19]. Thus, determining the pollution flashover characteristics of composite crossover insulators with a large diameter is important. In this study, an artificial pollution test is performed for AC composite crossarm insulators with voltage grades 66 kV to 1000 kV to determine their pollution flashover characteristics. Then, the effects of surface hydrophobicity state, core diameter, umbrella structure, arrangement form, and insulation distance on pollution flashover voltage are analyzed. This study may serve as technical support for designing and optimizing the electrical structure of composite crossarm insulators.

2. Test Equipment, Sample, and Method

2.1. Test Equipment

The artificial pollution test for composite crossarm insulators under power frequency voltage hereof is conducted in the large-scale environmental climate lab at the extra-high voltage AC test base. With a clear height of 25 m and a diameter of 20 m, the equipment tank is provided with a TYDZ-4800 kVA/10.5 kV voltage regulator and a YDTCW-6000 kVA/3 $\times$ 500 kV test transformer with a rated voltage of 10 kV and a rated current of 600 A at the primary side, and a rated voltage of 500 kV/1000 kV/1500 kV and a rated current of 10 A/6 A/1 A at the secondary side. All above test equipment follows power requirements for AC pollution test under IEC 60507-2013 [20].

2.2. Sample Parameters and Arrangement

The samples hereof include four types of composite crossarm insulators with core diameters of 100, 200, 300, and 450 mm, which correspond to voltage grades 66, 330, 500, and 1000 kV, respectively. Figure 1 shows the sample structure. In Table 1, the creepage factor (CF) is the ratio of the total creepage distance to the insulation distance of the insulator. Table 2 shows the structural parameters.

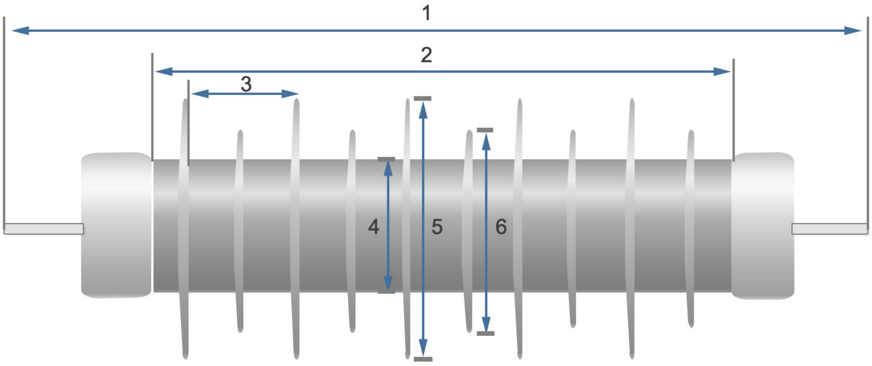


Figure 1. Schematic of sample structure. 1—structure height; 2—insulation distance; 3—shed spacing; 4—core diameter; 5—big shed distance; 6—small shed distance.

Table 1. Composite crossarm insulator parameters.

Voltage Grade (kV)	Core Diameter (mm)	Insulation Height (mm)	Creepage Distance (mm)	Umbrella Skirt Diameter (mm)	Umbrella Distance (mm)	CF
66	100	1 005	3 728	208/152	98/32	3.71
330	200	2 514	9 194	328/296	72/36	3.66
500	300	5 115	19 800	442/408	72/36	3.87
1 000	450	8 633	32 160	571/539	72/36	3.73

Table 2. Parameters of pollution flashover voltage curve.

Voltage Grade/kV	A	α	Degree of Fitting R^2
66	43.88	0.492	0.998
330	124.72	0.391	0.993
500	266.22	0.292	0.996
1 000	575.45	0.202	0.999

The sample of the artificial pollution test for the composite crossarm insulators is arranged horizontally, which is consistent with the practical operation state. Figure 2 shows the arrangement of a typical sample.

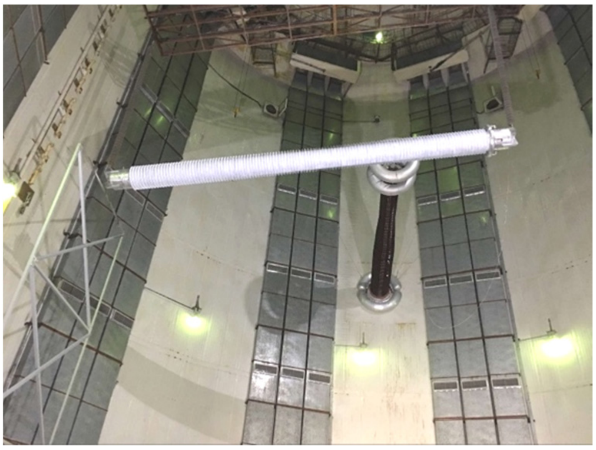


Figure 2. Sample arrangement.

2.3. Test Method

The artificial pollution test for the composite crossarm insulators with a large diameter is conducted with the solid chromatography recommended under IEC 60507-2013—"artificial pollution tests on high-voltage ceramic and glass insulators to be used on AC systems" [20]. In the test, commercially available NaCl with a purity of 99.5% and kaolin serve as the soluble salt and inert deposit, respectively, in the simulated deposit.

On the composite crossarm insulators hereof, the umbrella skirt and sheath are made of silicone rubber with good surface hydrophobicity. If the composite insulators' complete loss of surface hydrophobicity under extreme conditions is simulated on-site, kaolin can be applied on the surface to decrease its hydrophobicity, and then pollution coating is applied after complete loss of hydrophobicity. The test is conducted immediately after the pollution layer on the sample has dried [21,22]. If the surface state of the composite crossarm insulators from Grade HC5 to HC6 with weak hydrophobicity is simulated, kaolin is used to reduce surface hydrophobicity, and then pollution coating is applied. Based on temperature and humidity differences in the static environment of the samples, the test is often conducted after the sample has been drying for 4 h to 12 h. In this period, surface hydrophobicity is tested every 1 h. If the surface state satisfies the requirements, the test can be conducted.

In the artificial pollution test, boosting mode includes the constant-voltage lifting and lowering method and the uniform boosting method, where the constant-voltage lifting and lowering method is recommended as the national standard because it is closer to practical operation conditions and shows small data dispersity. The test time of the uniform boosting method is short, but the method is quite different from the actual working conditions and the data is scattered, so it is no longer recommended as a standard method. Therefore, this study uses the IEC 60507-2013-recommended constant-voltage lifting and lowering method to calculate 50% pollution flashover voltage (i.e., at least ten valid tests shall be conducted under standard pollution grade when test conditions are satisfied) and uses the uniform boosting method to quickly find the initial value of the voltage. Then, the 50% pollution flashover voltage U_{50} is calculated under the given pollution grade with the data of the above ten tests. The 50% pollution flashover voltage U_{50} and standard deviation σ are calculated as follows:

$$U_{50} = \sum_{i=1}^{N} U_i / N, \tag{1}$$

$$\sigma = \sqrt{\frac{\sum\limits_{i=1}^{N} (U_i - U_{50})^2}{N}} \times \frac{100\%}{U_{50}}, \tag{2}$$

where U_{50} is the 50% pollution flashover voltage of the composite crossarm insulators; U_i is the applied voltage level, kV; N is the frequency of valid tests; and σ is the relative standard deviation of test results.

3. Test Results and Analysis

3.1. Influence of Pollution Grade on Pollution Flashover Voltage

To determine the flashover characteristics of composite crossarm insulators with a large diameter under different pollution grades, this study conducts an artificial pollution test for composite crossarm insulators with four different core diameters. Considering the pollution grade in the applicable region of composite crossarm insulators, the non-soluble salt density deposit (NSDD) is determined to be 1.0 mg/cm^2, and the equivalent salt density deposition (ESDD) is determined to be 0.1, 0.2, and 0.25 mg/cm^2. Figure 3 shows the test results.

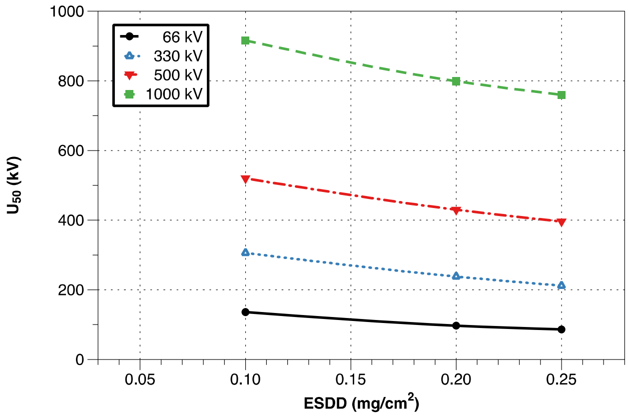


Figure 3. Pollution flashover test results of composite crossarm insulators with different voltage grades.

Test results show that the pollution flashover voltage of the composite crossarm insulators with four core diameters decreases in a nonlinear way with the increase in pollution grade. The relationship between pollution flashover voltage and pollution grade is expressed as below:

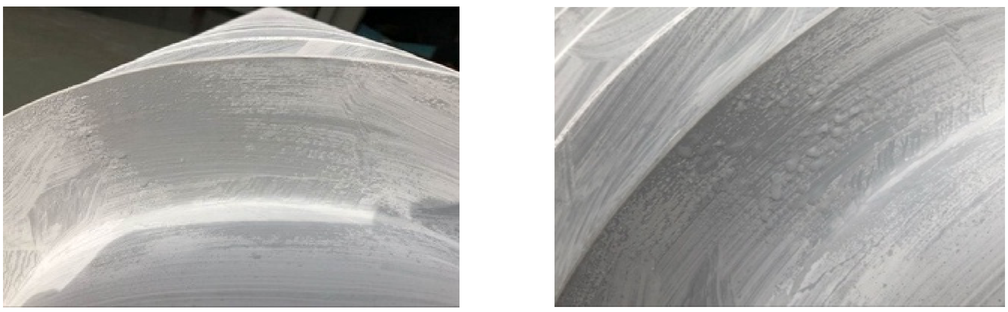
$$U_f = A\rho_{ESDD}^{-\alpha}, \tag{3}$$

where U_f is the pollution flashover voltage of the insulator, which is U_{50} hereof; A is the coefficient related to the insulator material and structure; ESDD is the equivalent salt deposit density; and α is the character index that represents the influence of ESDD on pollution flashover voltage.

Table 2 shows the parameters that are acquired through the fitting of the pollution flashover curve.

3.2. Influence of Surface Silicone Rubber State on Pollution Flashover Voltage

The surface state of a composite crossarm insulator largely influences its pollution flashover voltage [23,24]. To understand the influence of surface hydrophobicity state on pollution flashover voltage, this study conducts a pollution flashover test for composite crossarm insulators with a large diameter under surface hydrophilicity and weak hydrophobicity states. Figure 4a,b show the test results of the surface hydrophobicity state for a typical sample. Figure 4a shows the typical hydrophilicity state on the surface of silicone rubber. In accordance with STRI Guide 92/1 Hydrophobicity Classification Guide, the water film covers the whole test area, reaching hydrophobicity grade HC7. Figure 4b shows the typical weak hydrophobicity state on the surface of silicone rubber. The wet area is larger than 2 cm^2. The specific value between the water film area and the test area is close to 90%, and a small dry area can be observed. Thus, the hydrophobicity grade varies from HC5 to HC6.



(**a**) (**b**)

Figure 4. Hydrophobicity state of the sample surface: (**a**) HC7; (**b**) HC5~6.

Considering the pollution level of the area where the composite crossarm is applicable, 0.2/1.0 mg/cm^2 is selected as the test pollution degree, and the following test pollution degree is consistent with this. Table 3 and Figure 5 show the comparison of pollution flashover results under the above two states. Figure 6 shows the trends of a typical leakage current of 500 kV composite crossarm insulators with a diameter of 300 mm under hydrophilicity and weak hydrophobicity states on the surface of silicone rubber.

Table 3. Pollution flashover test results of composite crossarm insulators under hydrophilicity and weak hydrophobicity states.

Voltage Grade (kV)	Hydrophilicity (HC7)		Weak Hydrophobicity (HC5–HC6)	
	U_{50} (kV)	σ(%)	U_{50} (kV)	σ(%)
66	97.2	4.9	112.5	5.7
330	238.0	4.8	288.6	6.2
500	430.6	5.2	508.8	5.6
1000	798.6	5.5	906.3	6.1

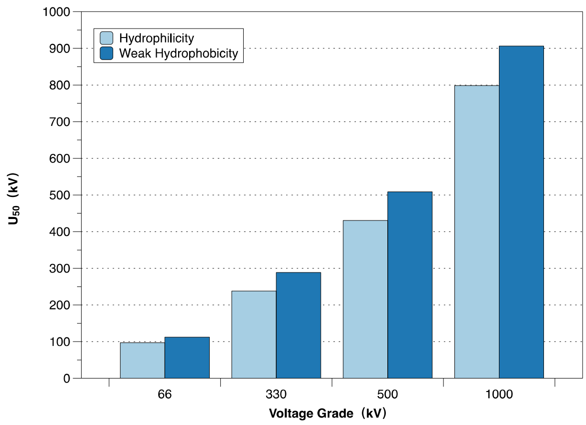


Figure 5. Comparison of pollution flashover test results of composite crossarm insulators with different hydrophobic states.

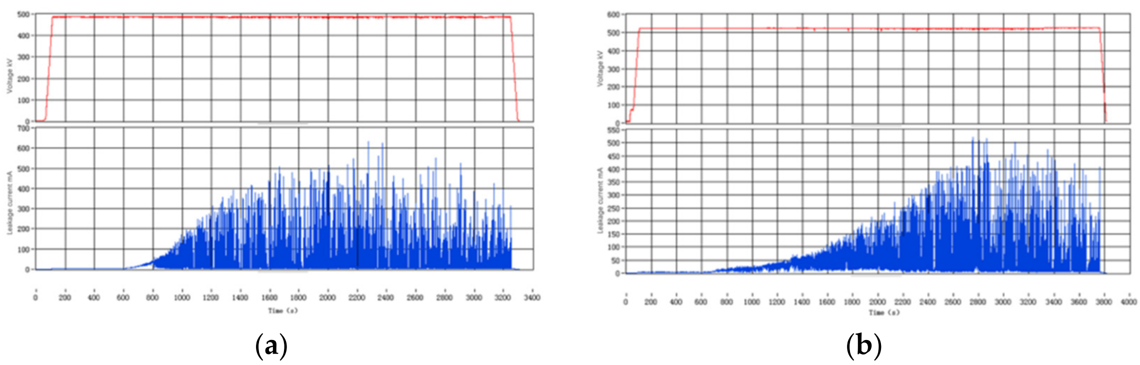


Figure 6. Leakage current trend: (**a**) Hydrophilicity state; (**b**) Weak hydrophobicity state.

As shown in Table 3 and Figure 5, the pollution flashover voltage of the composite crossarm insulator under a weak hydrophobicity state on the surface of silicone rubber is significantly higher than that of the insulator under a hydrophilicity state. In addition, the pollution flashover voltage of the four types of composite crossarm insulators under a weak hydrophobicity state has increased by 13.5% to 21.0% compared with those under a hydrophilicity state.

Leakage current can directly reflect arc size [25–27]. According to the leakage current trends in Figure 6, the surface state of composite crossarm insulators can influence the occurrence time, amplitude, and frequency of the arc. Under a hydrophilicity state, significant discharge can be observed within 10 min because surface pollution coating is easily wet by steam fog. Under a weak hydrophobicity state, the occurrence of significant discharge is several minutes later than under the hydrophilicity state because surface pollution coating cannot be wet by steam fog easily. In addition, the leakage current under the hydrophilicity state in the test is significantly higher than that under the weak hydrophobicity state. Combined with the trends of leakage current in the test, this paper analyzes the difference in pollution flashover performance under hydrophilicity and weak hydrophobicity states. The main reason is that the difference in the hydrophobic performance of pollution coating influences the wetting and arc development of samples [28,29]. In the wetting process, continuous water film can be formed easily on the hydrophilic surface, whereas scattered water drops can form on a strong hydrophobic surface. The water drop and water film can form on weak hydrophobicity surfaces with intermediate hydrophobicity performance. In the arc development process, the dry area on the lower surface with hydrophilicity is concentrated, indicating regional concentration for arc discharge. Due to the distortion effect of water drops on the electric field on the lower surface with hydrophobicity, multi-point discharge may be generated in the flashover process, forming a reticular dry area. In addition, surface discharge is scattered. Thus, multiple discharge branches consume certain energy. A single main arc is difficult to form because of the scattered effect of the discharge arc. As a result, the flashover voltage on the hydrophobicity surface is significantly higher than that on the hydrophilicity surface. For the weak hydrophobicity performance between complete hydrophilicity and strong hydrophobicity states, discharge on the hydrophilic and hydrophobic surfaces can occur in the flashover process, forming regionally concentrated discharge and scattered water drop discharge. That is to say, if the surface hydrophobicity of the composite crossarm insulator is worse, the weak discharge ratio decreases slightly, and the discharge of intermittent arc is transformed into continuous arc discharge, resulting in increased discharge ratio for continuous arc and then flashover. Therefore, the anti-pollution flashover performance of composite crossarm insulators with weak hydrophobic surfaces is significantly higher than those with hydrophilic surfaces.

3.3. Influence of Core Diameter on Pollution Flashover Voltage

The largest difference among selected composite crossarm insulators under different voltage grades hereof is in the core diameter. The gradient of pollution flashover voltage and creepage distance of the samples are calculated to determine the direct influence of core diameter on pollution flashover voltage. Table 4 shows the test results. Figure 7 shows the comparison results of voltage gradient and creepage ratio.

Table 4. Pollution flashover test results of composite crossarm insulators with different core diameters.

Voltage Grade (kV)	Core Diameter (mm)	U_{50} (kV)	σ (%)	Voltage Gradient (kV/m)	Creepage Ratio (mm/ kV)
66	100	97.2	4.9	96.7	38.6
330	200	238.0	4.8	94.7	39.6
500	300	430.6	5.2	84.0	46.0
1 000	450	798.6	5.5	92.5	40.3

Table 4 and Figure 7 show the results of the pollution flashover voltage test for composite crossarm insulators under different voltage grades. As shown in Figure 6a, under the same pollution grade, a 66 kV composite crossarm insulator with a core diameter of 100 mm has a pollution flashover voltage gradient of 96.7 kV/m and shows the best anti-pollution flashover performance, whereas a 500 kV equivalent composite crossarm insulator with a core diameter of 300 mm has a pollution flashover voltage gradient of

84.0 kV/m and shows the worst anti-pollution flashover performance. In the range of core diameter from 100 mm to 300 mm, the voltage gradient decreases with an increase in core diameter. If the core diameter is larger than 300 mm, the voltage gradient increases with the core diameter. The test results are converted into creepage ratio to eliminate the influence of umbrella structure and creepage ratio on pollution flashover results. Figure 6b shows the relationship between creepage ratio and core diameter. If the core diameter varies from 100 mm to 300 mm, the creepage ratio increases with core diameter. If the core diameter is larger than 300 mm, the creepage ratio decreases with the increase in core diameter.

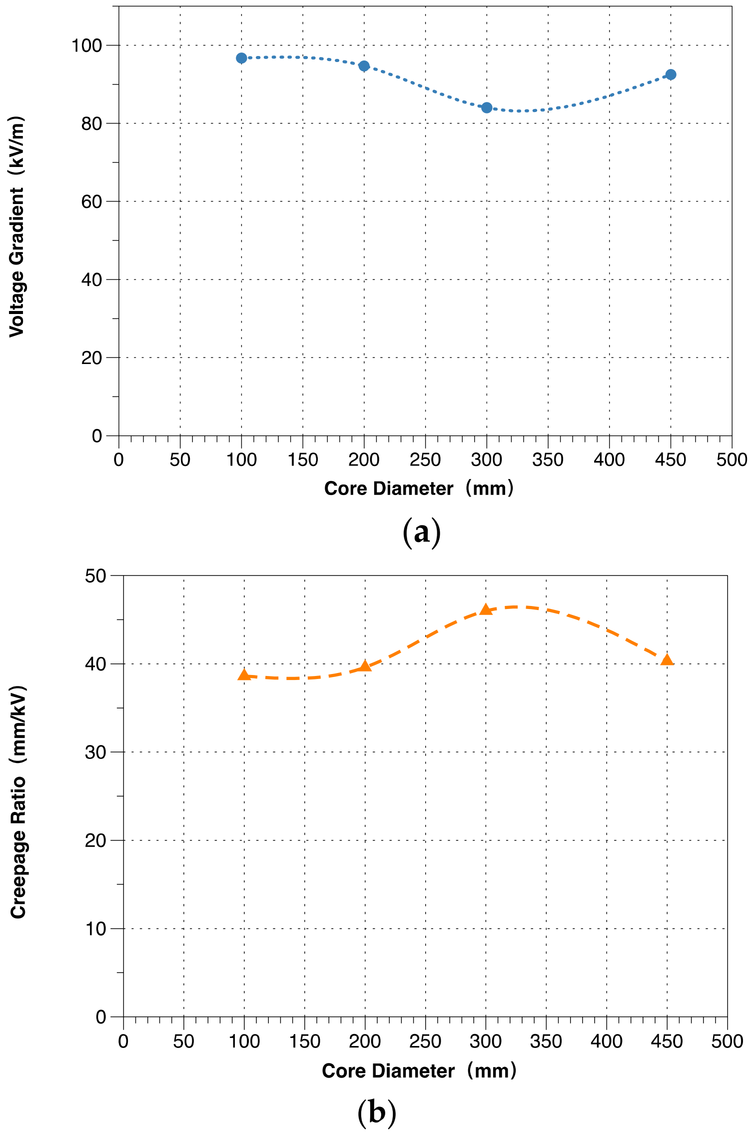


Figure 7. Results of pollution flashover tests: (**a**) Trends of voltage gradient and core diameter; (**b**) Trends of creepage ratio and core diameter.

The rod diameter influences the resistance performance of pollution coating. If other parameters are the same, the resistance of pollution coating increases with leakage distance but decreases with increasing diameter [26,30]. However, the pollution flashover voltage gradient of composite crossarm insulators under different voltage grades has no similar relationship to diameter. Therefore, other influencing factors shall be further studied.

3.4. Influence of Umbrella Structure on Pollution Flashover Voltage

Four groups of samples with the same insulation height and core diameter but different creepage distances, umbrella structures, and umbrella distances are customized to study the influence of umbrella structure on pollution flashover voltage. Samples #1 to #3 are designed with one large umbrella and one small umbrella structure, of which the difference is the diameter of the umbrella skirt and umbrella distance. Sample #4 is designed with one large umbrella and two small umbrella structures. Table 5 shows the structure parameters.

Table 5. Structure parameters.

No.	Insulation Height (mm)	Core Diameter (mm)	Creepage Distance (mm)	Diameter of Umbrella Skirt (mm)	Umbrella Distance (mm)	CF
#1	1 060	220	3 983	356/322	72/36	3.76
#2	1 060	220	3 961	334/294	60/30	3.74
#3	1 060	220	3 971	394/354	96/48	3.75
#4	1 060	220	4 051	378/318	108/36	3.82

Table 6 shows the results of flashover tests for the samples. As listed in Table 5, sample #1 is featured with optimal anti-pollution flashover performance, with a 50% pollution flashover voltage of 110.5 kV. Under the same insulation height and diameter and CF value range from 3.74 to 3.82, the difference in pollution flashover voltage of the four types of crossarm insulators with umbrella structure varies from 1.7% to 5.4%, and the umbrella structure has a minimal influence on the pollution flashover voltage of composite crossarm insulators.

Table 6. Influence of umbrella structure on pollution flashover test results of composite crossarm insulators.

No.	U_{50} (kV)	σ (%)	Voltage Gradient (kV/m)	Creepage Ratio (mm/kV)
#1	110.5	5.1	103.8	36.0
#2	106.6	4.6	100.5	37.1
#3	104.8	4.3	98.9	37.9
#4	108.2	5.3	102.1	37.4

3.5. Influence of Arrangement on Pollution Flashover Voltage

Another significant difference with common composite insulators is the arrangement form. Composite crossarm insulators are mainly arranged in horizontal form, whereas composite insulators are usually arranged in a vertical way. To study the influence of arrangement form on the pollution flashover voltage of composite crossarm insulators with a large diameter, this study conducts a flashover comparison test under a vertical arrangement for samples #1 and #2 in Section 3.3. Table 7 shows the test results.

Table 7. Influence of arrangement on pollution flashover test results of composite crossarm insulators.

No.	Horizontal Arrangement		Vertical Arrangement	
	U_{50} (kV)	σ (%)	U_{50} (kV)	σ (%)
#1	110.5	5.1	98.6	4.5
#2	106.6	4.6	96.5	4.9

Under the same test conditions, the pollution flashover voltage of the composite crossarm insulators is higher under horizontal arrangement than under vertical arrangement. For samples #1 and #2, the pollution flashover voltage under horizontal arrangement increases by 12.1% and 10.5%, respectively, compared with that under the vertical arrangement. The main reason is the difference in pollution loss degree. In the flashover test, the surface pollution on silicone rubber is wet by hot fog to form a high-conductivity water film. Due to gravitation, the water film on the top and bottom surfaces of pollution coating on the composite crossarm insulator under horizontal arrangement can clean the surface of the umbrella sheath and then flow away directly along the sheath, resulting in a serious loss of deposits. It is different for samples under the vertical arrangement. The surface deposit flows away and along the umbrella sheath in the wetting process. The water film cannot play a better cleaning role, and the angle of inclination at the lower surface of the umbrella sheath is small. As a result, the water film cannot be formed on the surface, and deposits cannot flow away easily. Therefore, the loss degree of deposits is lower than the one under the vertical arrangement. These factors decrease the pollution flashover voltage of composite crossarm insulators under the vertical arrangement.

3.6. Relationship between Insulation Distance and Pollution Flashover Voltage

Domestic and foreign scientific research institutions have focused on the relationship between the string length of suspension insulators and pollution flashover voltage. Results show that the pollution flashover voltage of suspension insulators has an approximately linear relationship with string length. However, considering different size structures and arrangement forms, this study conducts an artificial pollution test for 1/4, 1/2, and 3/4 short circuits of EHV composite crossarm insulators to study the relationship between the insulation distance and pollution flashover voltage of composite crossarm insulators with a large diameter. In the test, the surface states of the samples include hydrophilicity and weak hydrophobicity. Figure 8 shows the test results.

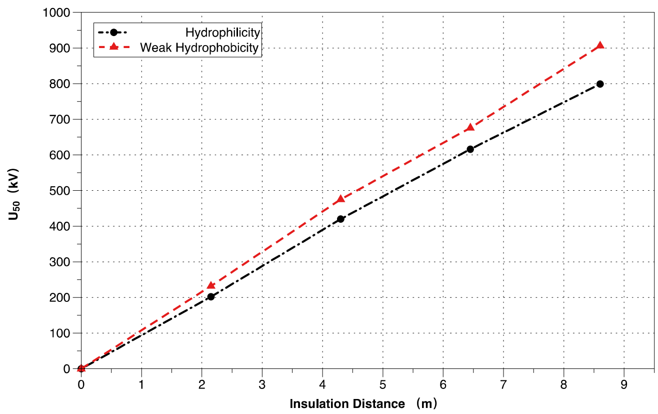


Figure 8. Pollution flashover test results of composite crossarm insulators with different insulation distance.

In the range of insulation distance from 0 m to 8.6 m, the pollution flashover voltage of the composite crossarm insulators with a large diameter under hydrophilicity and weak hydrophobicity states has an approximately linear correlation with insulation distance. The relevance of linear fitting is R12 = 0.999 0 and R22 = 0.999 2, respectively.

In sum, the surface hydrophobicity state of silicone rubber, rod diameter, creepage distance, umbrella structure, and arrangement form can influence the pollution flashover voltage of composite crossarm insulators with a large diameter, where the surface hydrophobicity state, core diameter, creepage distance, and arrangement form exert a large influence on pollution flashover voltage.

4. Conclusions

The presented paper illustrated the influence of composite crossarm insulator core diameter, surface hydrophobicity, umbrella structure, arrangement, and insulation distance on the pollution flashover voltage of large diameter composite crossarm insulators through artificial pollution tests. In the range of core diameter from 100 mm to 450 mm, the pollution flashover voltage gradient decreases with the increase of core diameter and then increases with the increase of core diameter. The hydrophobicity of the surface can significantly increase the pollution flashover voltage, and the influence of the hydrophobicity of the surface should be considered in the external insulation configuration of the project. When the CF value is close, the umbrella structure has little effect on the pollution flashover voltage. Under the same test conditions, the pollution flashover voltage of horizontally arranged composite crossarm insulators is higher than that of vertical ones. The pollution flashover voltage of composite crossarm insulators has an approximately linear relationship with the insulation distance. The above factors need to be considered comprehensively in the structural design of composite crossarm insulators. The pollution flashover of composite crossarm insulators is a complex process that is influenced by multiple factors. Thus, tests are performed to study the pollution flashover voltage. In the future, methods of pollution flashover tests, arc development process, and trends of leakage current of composite crossarm insulators with a large diameter shall be further studied to assess the mechanism underlying their flashover performance.

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