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The Shed Hole Influence on the Electrical Performance of Composite Insulator

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ABSTRACT In recent years, shed holes appeared on the surface of in-service composite insulators have been observed in transmission lines in the southern and middle regions of China. Their presence can shorten the insulator creepage distance and therefore may impair the composite insulator's electrical performance. In this paper, extensive experiments were carried out to study the influence of shed hole (shed hole diameter, shed hole arrangement, shed hole percentage) on the electrical performance including pollution flashover voltage, pollution-rain flashover voltage, dry flashover voltage, wet flashover voltage, and lightning impulse voltage. The experimental results showed that the presence of shed hole had insignificant impact on the dry flashover voltage, wet flashover voltage, and lightning impulse when the shed diameter was 1.0 mm. However, the shed hole influence on the pollution flashover and pollution-rain flashover performance was appreciable. When the shed hole diameter is 1.0 mm, both the pollution flashover voltage and the pollution-rain flashover voltage are higher with alternating arrangement than that with straight-line arrangement. With the same shed hole diameter and pollution degree, the electrical performance of pollution-rain flashover is better than the pollution flashover. It is also found that the diameter of shed hole is increased by 3% to 60% after the pollution flashover test.

INDEX TERMS Composite insulator, electrical performance, pollution, lightning impulse, shed hole.

I. INTRODUCTION

Since 1980s, silicone rubber composite insulator has been widely used in the high voltage transmission system for its light weight, high mechanical strength, and ease of installation [1], [2]. Although the flashover performance of composite insulator under icing condition is slightly inferior to that of conventional porcelain or glass insulators, its pollution flashover is much better than the latter in the heavily polluted regions under wet condition [3]–[6]. In three ultra-high voltage (UHV) AC transmission lines which were put into service in China in 2016, the proportion of composite insulators consisted of about 60 % of all line insulators. In the six UHV DC transmission lines that were built up recently, that proportion was even up to 85 %. At the end of 2016, there were about 800 million composite insulators been used in the AC and DC transmission system with nominal voltage rated from 110 kV to 1100 kV in China [7], [8].

Although great progress has been made in the composite insulator technology, there are still many problems need to be resolved. Since they are normally operating outdoors, their mechanical and electrical properties could be degraded for being subjected to adverse environmental conditions such as high electric field strength, high temperature, and severe pollution, etc. [9]. On October 30, 2015, a routine inspection of Line Xiaozong was conducted by helicopter. This line was put into operation at 220 kV on June 12, 2011 and then partly upgraded to 500 kV. During the inspection, temperature rises from 3.3 K up to 11.4 K were observed at the high voltage ends of composite insulators suspended on tower #N242. On November 14, 2015, all twelve composite insulators were replaced from tower. After a careful check, it was found that

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FIGURE 1. Shed holes of the composite insulators. (a) 550 kV composite insulator replaced from Tower #N242 of Line Xiaozong; (b) 220 kV composite insulator replaced from Tower #N25 of Line Huiqing.

about 12 to 22 shed units at the high voltage ends of all composite insulators had shed holes. That was about 27.9% to 51.1% of the total shed number. A typical shed hole is shown in Figure 1(a). On March 13, 2017, Line Huiqing, which operated at 220 kV, was tripped and shed holes were found on composite insulators installed on tower #N25, as shown in Figure 1(b). Similar shed hole phenomena were also reported in Haigang 220 kV transmission lines in Zhuhai, Guangdong and many other high-voltage transmission lines. According to the observation, the shed hole diameter of collected defective insulators ranged from 0.2 mm to 2.4 mm and they were located near the rod as illustrated in Figure 1. These shed holes are quite different from the typical housing erosion and aging from the appearances and their locations. Many researchers investigated the formation of shed holes. The shed hole phenomenon was reproduced in the laboratory after 30, 000 cycles of track wheel test [10]. After careful observation, it was concluded that the burning of arcs was the main reason for their formation. When subjected to such a high-temperature arc root which could be higher than 1000 °C for a certain time, the insulation material was pulverized and carbonized [11]. It was also found that shed holes were more likely to be formed if the crosslinking agents could not react completely during the curing process of the silicone rubber.

Although the observation of shed holes can date back to 1980s [12], most of research were focused on the defect detection and aging evaluation. Up to now, little literature can be found on the flashover performance of the composite insulators having shed holes. As the presence of shed holes may short out the sheds thereby reducing the creepage distance, the main objective of this study is to investigate the electrical performance of composite insulators with shed holes under various adverse conditions. In this paper, three types of new composite insulators were acquired and shed holes were made artificially. Various flashover tests were carried out in the chamber and outdoor. The test results of this paper may give guidance to the maintenance of composite insulators.

II. TEST FACILITIES, SPECIMENS, AND PROCEDURES

A. TEST FACILITIES

In this paper, five types of experiments, namely lightning impulse, pollution, pollution-rain, dry and wet flashover tests

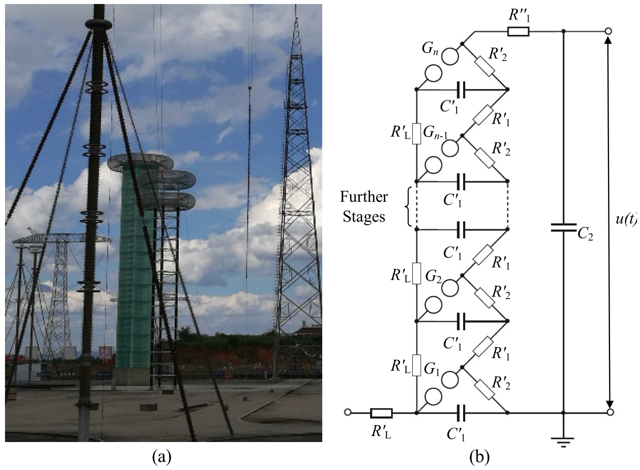
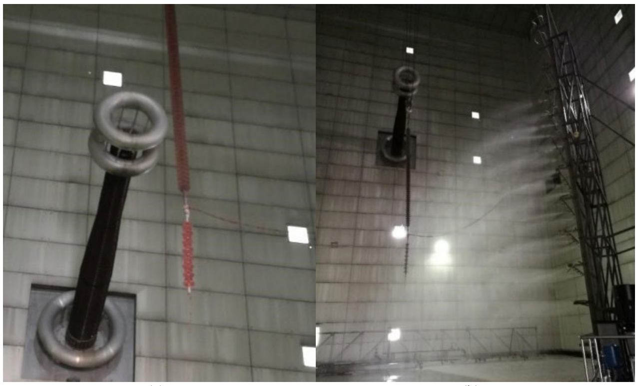


FIGURE 2. Outdoor UHV laboratory in Kunming, China. (a) Impulse voltage generator; (b) Equivalent circuit of multi-stage impulse generator.

were carried out to study the electrical performance of composite insulators that had shed holes on their sheds. The purpose of lightning impulse test is to secure that the transmission lines withstand the lightning overvoltage which may occur in service. A type of 110 kV composite insulator was tested, and the test was performed outdoor at National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, China) with an altitude of 2100 m. The experimental setup and its equivalent test circuit are shown in Figure 2. The maximum charging voltage is 200 kV per stage with a maximum energy of 20 kJ. With 36 stages, the impulse voltage generator has a total charging voltage up to 7.2 MV and a total charging energy up to 720 kJ. It can generate standard lightning impulse (1.2/50 μs), standard switching impulse (250/2500 μs), and switching impulse with front time of 2,000 μs or even longer. The uncertainties of measurement amounted to 2.5 % for the test voltage value (peak value), which is in accordance with IEC standard 60060 and IEEE St.4 [13]–[15].

The pollution and pollution-rain flashover tests of composite insulators with rated voltages of 500 kV were performed in a fog chamber at National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, China). The fog chamber is illustrated in Figure 3. It is one of the highest performances in the world allowing pollution test of up to 800 kV AC and 1,000 kV DC. It has a dimension of 26 m (width) × 26 m (length) × 30 m (height). In these tests, the power was supplied by a 4800 kVA/800 kV test transformer which met the requirements recommended in [13]–[15]. For pollution tests, the steam fog was generated with an input rate of 0.05 ± 0.01 kg/(h·m^3) by a boiler. Considering the chamber has a volume of 20,280 m^3, the steam output should be at least 1014 kg/h. To achieve the desired fog intensity, the boiler was designed to have a capacity of 1500 kg/h. To carry out the pollution-rain tests, 13 sets of nozzles are mounted on a stand as displayed in Figure 3(b). The distance between two adjacent nozzle sets is 0.6 m, and each set has three nozzles. The rainfall intensity can be adjusted by regulating the air



(a) (b)

FIGURE 3. **Fog chamber of UHV laboratory in Kunming, China. (a) Pollution flashover test; (b) Pollution-rain flashover test.**

(a) (b)

FIGURE 4. **Test facilities at Electric Research Institute in Jiangsu, China. (a) AC power supply; (b) Fog chamber.**

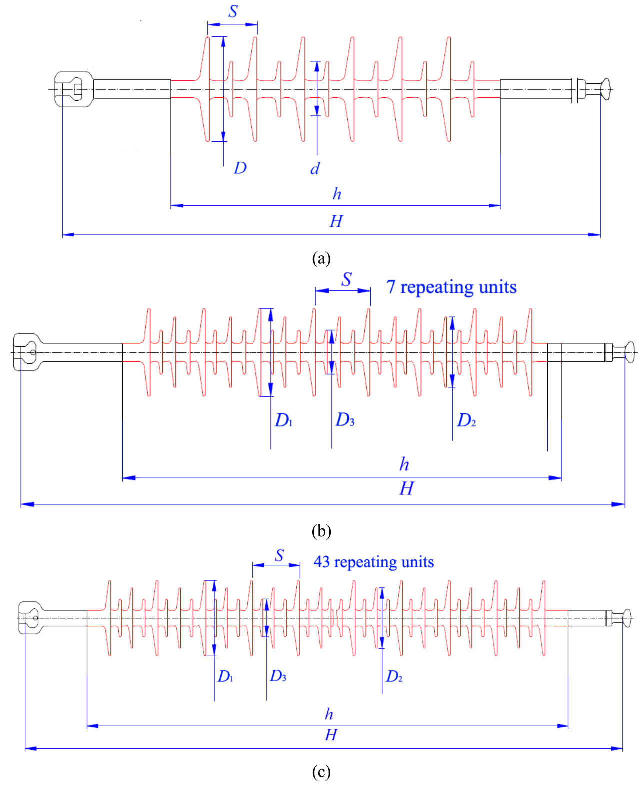


FIGURE 5. **Profiles of the tested specimen. (a) FXBW-35/70; (b) FXBW4-110/100-A; (c) FXBW4-500/240-C.**

TABLE 1. **The profile parameters of tested composite insulators.**

Insulator Type	Structure Height H (mm)	Arcing Distance h (mm)	Leakage Distance L (mm)	Shed Spacing S (mm)	Shed Diameter $D_1/D_2/D_3$ (mm)
A (FXBW-35/70)	660	464	1015	70	100/-/70
B (FXBW4-110/100-A)	1240	1000	3200	105	162/130/86
C (FXBW4-500/240-C)	4750	4300	14750	96	140/110/80

TABLE 2. **The test insulators, flashover test types and test methods.**

Insulator Type	Test Site	Test Type	Test Method
A (FXBW-35/70)	Chamber, Jiangsu	Pollution flashover	Up-and-down
B (FXBW4-110/70-A)	Outdoor, Kunming	Lightning Impulse	Up-and-down
B (FXBW4-110/70-A)	Chamber, Kunming	Dry flashover Wet flashover	Ever-rising Ever-rising
C (FXBW4-500/240-C)	Chamber, Kunming	Pollution flashover Pollution-rain flashover	Up-and-down Up-and-down

and water pressure gauges. The dry flashover test and wet flashover test of 110 kV composite insulators were also tested in this chamber.

The pollution flashover tests of 35 kV composite insulators were carried out at Electric Power Research Institute in Jiangsu, China, as shown in Figure 4. The power was supplied by a 2400 kVA/600 kV test transformer as shown in Figure 4(a). It also satisfied the requirement specification in [13]–[15]. The fog chamber in Figure 4(b) has an area of 14 m^2 and a height of 4 m.

B. SPECIMENS

Three types of composite insulators, namely FXBW-35/70, FXBW4-110/70-A, and FXBW4-500/240-C, were tested in this study. For ease of reading, they are labeled as Type A, Type B, and Type C. The profiles of these insulators are illustrated in Figure 5 with their detailed profile parameters listed in Table 1. The basic insulation levels (BIL) of these three types of composite insulators were 250 kV, 550 kV and 2410 kV, respectively.

C. PROCEDURES

To ensure the desired performance of the composite insulator, which is for avoiding unwanted insulator failure, various flashover tests were performed at different sites as indicated in Table 2. In the lightning impulse, pollution, and pollution-rain tests, the up-and-down method was adopted to obtain the 50% flashover voltage $U_{50\%}$ with a step (ΔU) of 5% of the last flashover voltage (or the expected flashover voltage in the first try). In each test, the next voltage is determined by the last test result. If the last trial voltage withstands, the next trial voltage is increased by ΔU. Otherwise, it is decreased accordingly. The first trial voltage showing a different test result from the last one (from withstand to flashover or vice versa) and the following tests are defined as valid tests [16]. For each sample, at least 10 valid tests are performed. Then, the $U_{50\%}$ and the relative standard deviation (RSD) σ can be calculated by:

$$U50\% = \frac{\sum_{i=1}^{N} Ui}{N} \tag{1}$$

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

where U_i is the i^{th} valid test voltage and N is the number of valid tests.

The ever-rising method was used in the dry flashover test and wet flashover test due to its advantage in obtaining large number of test results in a relative short time. Using this method, the applied voltage is first increased at a high rate to 75% of the estimated flashover voltage U_e. After that, the voltage increase rate is changed to 2%U_e/s until flashover happens [17]. Then, the flashover voltage U_r is calculated by averaging the values of all valid tests, which is similar to Eq. (1).

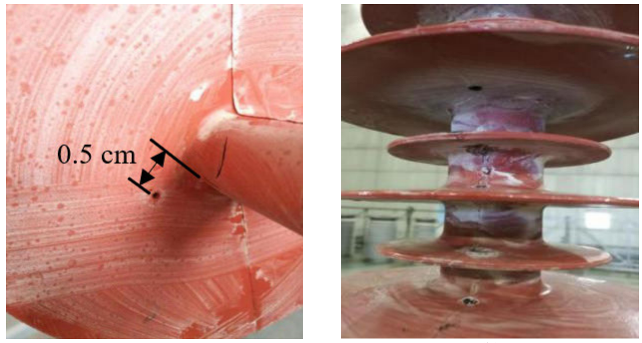
As the flashover voltage is related to the atmospheric conditions such as air pressure, the measured voltage U is corrected to the flashover voltage at sea level by:

$$U_0 = U \cdot (\frac{P}{P_0})^{-m} \tag{3}$$

where U is the flashover voltage at low air pressure (high altitude), U_0 is the flashover voltage at standard pressure at sea level (101.3 kPa), and m is a constant characterizing the influence of air pressure on the flashover voltage which is 0.58 for lighting impulse test and 0.54 for AC flashover test [18].

In the lightning impulse test, clean composite insulators of type B were conducted with the IEC Standard impulse wave of 1.2/50 μ s and the detailed test procedure can be found in IEC 60060 [19], [20].

In the pollution test, the insulator was first cleaned with care to make sure that all traces of dirt and grease were removed. After that, the insulator surface was artificially polluted using the solid layer method. To simulate the pollution, sodium chloride (NaCl) was used to represent the soluble material while kaolin was chosen to represent the insoluble component. The mixture of weighted NaCl and kaolin was added into deionized water and then uniformly coated on the insulator surface by the pasting method [21]–[23]. The equivalent salt deposit density (ESDD) is normally used to characterize the pollution degree. Three ESDDs of 0.05 mg/cm^2, 0.10 mg/cm^2, and 0.15 mg/cm^2 were carried out in the pollution test. In all pollution tests, the non-soluble deposit density (NSDD) was 1.0 mg/cm^2. It should be mentioned that before the first contamination, the insulators were scrubbed with a slurry of water and kaolin and then thoroughly rinsed with tap water. Before applying the voltage, the insulator was wetted by steam fog. Then, voltage was applied and increased at a rate of 2 kV/s to the test voltage. The voltage was maintained until flashover took place. Otherwise, it was maintained for 100 minutes from the start of the test or until there was obvious evidence to exclude the possibility of flashover by the leakage current. The pollution layer on the insulator surface was tested only once.



(a) (b)

FIGURE 6. Tested FXBW4-500/240-C insulator with shed holes. (a) Before pollution-rain test; (b) After pollution-rain test.

In the pollution-rain test, the insulator contamination process was the same with the pollution test and the flashover test was performed 15-18 hours after the insulator was contaminated. To create an artificial raining condition, the contaminated insulator was sprayed with water at a precipitation direction of 45°. The volume conductivity of water used for simulating the rain was 70 μS/cm and the precipitation intensity was 5 mm/min. As the contamination can be washed by the rain, each polluted insulator was used only once.

In the dry flashover test and wet (rain) flashover test, clean insulator specimens were used, and the ever-rising method was adopted. In addition, the precipitation direction and water resistivity in the wet flashover test were the same with the pollution-rain test while the precipitation intensity was 2 mm/min. The wet flashover test was carried out at least 15 min after the start of the rain.

To observe the arc development, the flashover process in the above-mentioned tests was recorded by an ultrahigh-speed camera Phantom v2012 which could reach up to 22, 500 fps at a resolution of 1280 × 800.

III. RESULTS AND DISCUSSION

In this paper, all shed holes were artificially made by an electric drill and the holes were located 0.5 cm away from the rod as displayed in Figure 6. The shed diameter was measured by a digital caliper from Sangabery which provided a resolution of 0.1 mm.

A. THE INFLUENCE OF SHED HOLES ON THE POLLUTION FLASHOVER PERFORMANCE OF COMPOSITE INSULATOR

Type A (35 kV) composite insulator was used to study the influence of shed holes on the pollution flashover performance. Three dimensions of shed holes with diameters of 0.5 mm, 1.0 mm, and 2.0 mm were artificially made. As the proportion of sheds that have holes may affect the pollution flashover performance, five proportions, namely 1/6, 1/3, 1/2, 2/3, and 100% were investigated. These shed holes were in

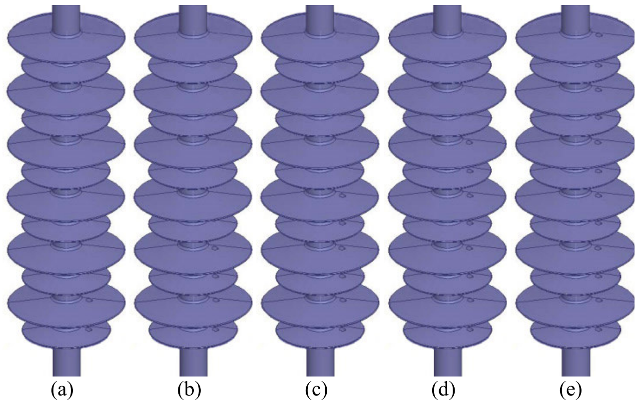


FIGURE 7. Schematic diagram of composite insulators with different shed hole proportions. (a) 1/6 (b) 1/3; (c) 1/2; (d) 2/3; (e) 100%.

TABLE 3. Results of pollution flashover voltage tests of 35 kV composite insulators with shed hole diameter of 0.5 mm.

Shed Hole Percentage	ESDD = 0.05 mg/cm²			ESDD = 0.10 mg/cm²			ESDD = 0.15 mg/cm²		
	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)
0	63.2	0.0	4.4	57.0	0.0	5.9	55.8	0.0	2.3
1/6	64.5	2.1	3.9	57.3	0.5	5.4	52.8	-5.4	5.8
1/3	64.7	2.4	5.7	57.7	1.2	2.8	53.0	-5.0	4.1
1/2	61.9	-2.1	1.3	59.3	4.0	5.2	51.8	-7.2	2.9
2/3	59.7	-5.5	2.7	57.6	1.1	1.7	49.7	-10.9	4.0
100%	58.2	-7.9	4.3	51.5	-9.6	4.1	46.8	-16.1	5.5
Bare Rod	30.1	-52.4	3.1	26.3	-53.9	2.2	24.4	-56.3	3.9

a straight-line arrangement as illustrated in Figure 7. In the former four proportions, the shed holes were started from the high voltage end. In addition, non-defective composite insulator without any shed hole and bare rod insulator with all sheds removed were also tested.

The test results at ESDD of 0.05 mg/cm^2, 0.10 mg/cm^2, and 0.15 mg/cm^2 are listed in Table 3 to Table 5. To describe the influence of shed holes, the flashover voltage of non-defective composite insulator with no shed hole is taken as the reference. Then, the percentage of voltage drop β is defined as:

$$\beta = \left(\frac{U_i - U_{nsh}}{U_{nsh}}\right) \times 100\% \tag{4}$$

where U_i is the pollution flashover voltage of composite insulator with shed holes or without sheds (bare rod), and U_{nsh} is the flashover voltage of non-defective composite insulator.

When the shed hole diameter is 0.5 mm and the ESSD is not greater than 0.10 mg/cm^2, the percentage of voltage drop is less than 5.5% as long as the shed hole percentage is less than 2/3. In these cases, the influence of shed holes on the pollution flashover performance is minor. By ultrahigh-speed camera, it was observed that the discharge path barely passed through the shed holes. After the tests, it was found that the

TABLE 4. Results of pollution flashover voltage tests of 35 kV composite insulators with shed hole diameter of 1.0 mm.

Shed Hole Percentage	ESDD = 0.05 mg/cm²			ESDD = 0.10 mg/cm²			ESDD = 0.15 mg/cm²		
	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)
0	63.2	0.0	4.7	57.0	0.0	2.9	55.8	0.0	3.7
1/6	61.5	-2.7	3.4	53.4	-6.3	3.7	50.0	-10.4	3.5
1/3	56.8	-10.1	3.8	49.7	-12.8	2.4	50.2	-10.0	2.8
1/2	54.0	-14.6	2.3	49.5	-13.2	3.2	47.8	-14.3	3.2
2/3	56.7	-10.3	3.0	47.1	-17.4	3.3	43.4	-22.2	4.8
100%	48.1	-23.9	3.7	48.2	-15.4	4.6	40.7	-27.1	5.1

TABLE 5. Results of pollution flashover voltage tests of 35 kV composite insulators with shed hole diameter of 2.0 mm.

Shed Hole Percentage	ESDD = 0.05 mg/cm²			ESDD = 0.10 mg/cm²			ESDD = 0.15 mg/cm²		
	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)
0	63.2	0.0	5.0	57.0	0.0	3.7	55.8	0.0	3.2
1/6	58.9	-6.8	4.5	53.8	-5.6	4.2	46.8	-16.1	5.2
1/3	55.4	-12.3	4.3	48.1	-15.6	3.9	45.0	-19.4	4.4
1/2	51.1	-19.1	1.9	44.7	-21.6	2.3	45.2	-19.0	2.7
2/3	51.1	-19.1	2.4	42.3	-25.8	1.7	39.1	-29.9	5.5
100%	52.1	-17.6	3.2	44.7	-21.6	5.1	37.9	-32.1	2.1

shed holes were almost blocked by the pollution, making the arc difficult to pass through.

In other tests, arcs passing through the shed holes were observed, especially when the shed hole diameter is large and ESDD is high. Moreover, the pollution flashover voltage generally decreases with the increase of shed hole percentage, shed hole diameter, and ESDD. When the shed hole diameter is 1.0 mm and 2.0 mm, the percentage of voltage drop can be as high as −27.1% and -32.1% if shed hole percentage is 100%. It should be noted that the Type A insulator can still withstand at the nominal voltage even in the condition that shed hole percentage is 100%, shed hole diameter is 2.0 mm, and ESDD is 0.15 mg/cm^2. When all the sheds are removed, the percentage of voltage drop can be up to −50%.

Figure 8 shows the insulator after the pollution flashover test. It can be seen clearly that the arcs have passed through the shed holes indicated in the red box and ablation traces are left. After the test, the insulators were cleaned and it was found that some shed hole diameters which initially had a diameter of 1.0 mm or 2.0 mm increased by 3% to 64%, depending on the time it withstands the arc.

Figure 9 shows one of the measured currents during the test. When there are shed holes, the leakage current is appreciable even long time before the flashover happens. Therefore, the presence of shed hole can greatly intensify the leakage current in the phase before flashover.

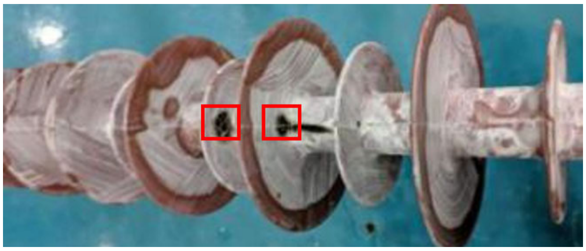


FIGURE 8. Tested FXBW-35/70 insulator after pollution test.

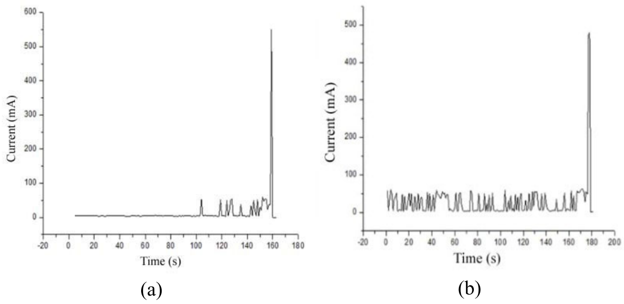


FIGURE 9. Measured leakage current of Type A insulators during the pollution flashover test. (a) Insulator without any shed hole; (b) Insulator with 1/2 shed holes.

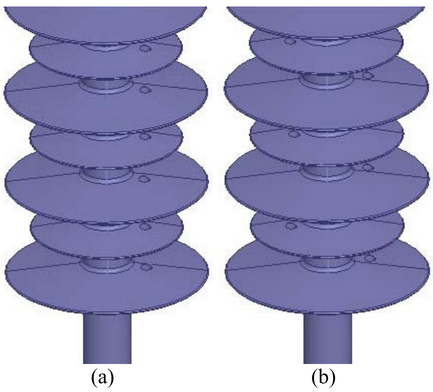


FIGURE 10. Schematic diagram of two shed hole arrangements (not to scale). (a) Straight-line arrangement; (b) Alternating arrangement.

In the above tests, the shed holes are in the straight-line arrangement. To check whether the shed hole arrangement would influence the pollution flashover performance or not, the alternating arrangement, as illustrated in Figure 10, was also studied with Type C (500 kV) composite insulator. In the tests, the ESDD was 0.10 mg/cm^2, the shed hole percentage was 2/3, and the shed hole diameter ranged from 1.0 mm to 3.0 mm. The test results are listed in Table 6. As can be seen from the table, the percentage of voltage drop β decreases with the shed hole diameter for both shed hole arrangements. When the shed hole diameter is 1.0 mm, there is a significant difference between two arrangements. The percentage of voltage drop is -9.3% for the alternating arrangement which is 9.4% lower than the straight-line arrangement. However, when the shed hole diameter is 2.0 mm or 3.0 mm, the difference between two arrangements is less than 2.7% which indicates that the shed hole arrangement no longer has an effect on the pollution flashover voltage.

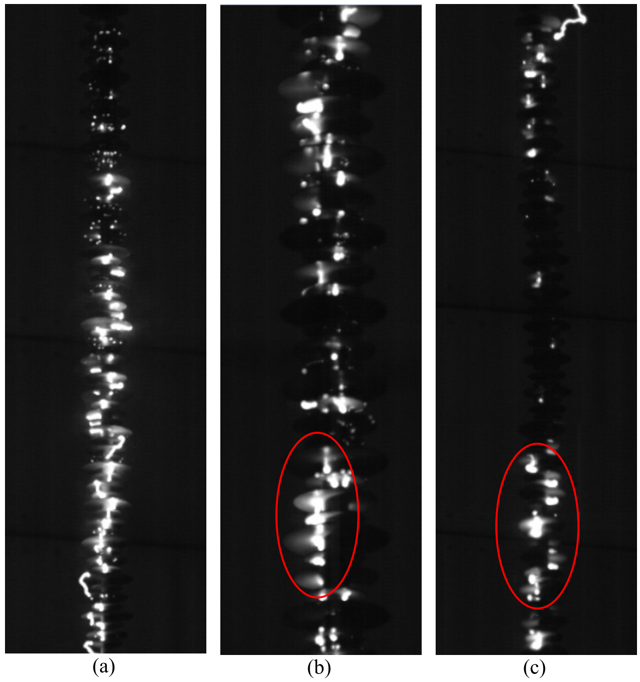


FIGURE 11. Discharge paths of three Type C composite insulators. (a) Insulator without shed hole; (b) Insulator with shed holes in straight-line arrangement; (c) Insulator with shed holes in alternating arrangement.

TABLE 6. Results of pollution flashover voltage tests of 500 kV composite insulator.

Shed Hole Diameter (mm)	$U_{50\%}$ (kV)	β (%)	σ (%)	Shed Hole Arrangement
0	332	0.0	4.7	No Shed Hole
1	270	-18.7	2.8	2/3 Shed Holes (Straight-line Arrangement)
2	264	-20.5	6.4	
3	255	-23.2	5.9	
1	301	-9.3	6.3	2/3 Shed Holes (Alternating Arrangement)
2	263	-20.8	1.9	
3	257	-22.6	4.3	

For a given insulator at a certain pollution degree, the leakage distance plays an importance role on the flashover voltage. Figure 11 shows the discharge paths of non-defective insulator and insulators with shed hole diameter of 1.0 mm with different shed hole arrangements. When there is no shed hole, the discharge path follows the insulator surface or floating in the air nearby as illustrated in Figure 11(a). Under this circumstance, the leakage distance is the longest and the pollution flashover voltage is the highest. When the shed holes are in the straight-line arrangement, discharge arcs passing through the shed holes were observed in the red oval in Figure 11(b), leading to a dramatic flashover voltage decrease. The detailed arc development passing through the shed holes are recorded as displayed in Figure 12. According to the observations, the arc passing through the shed

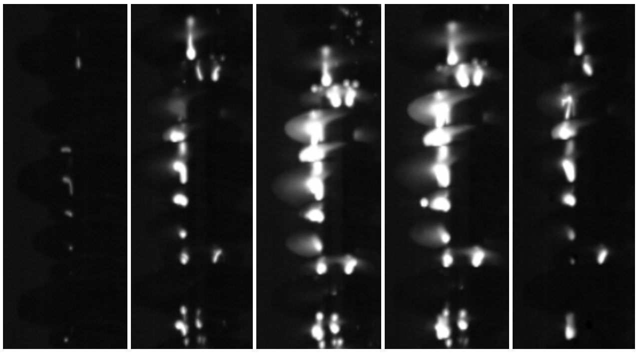


FIGURE 12. The development of discharge arcs passing through the shed holes.

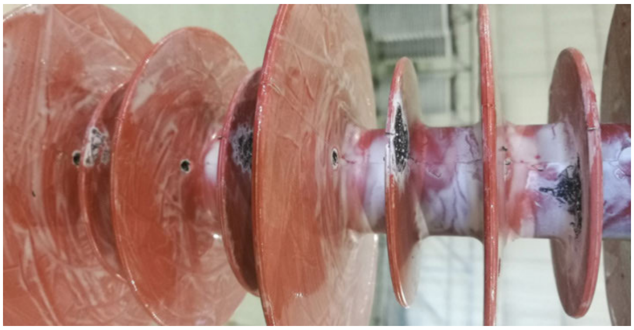


FIGURE 13. The appearance of FXBW4-500/240-C insulator after pollution test.

holes is more likely to happen near the high voltage end. In Figure 13, four of eight consecutive shed holes have been passed through by arcs at the high voltage end. Therefore, there is no guarantee that each shed hole will be shorted by the arc even the ESDD and the shed hole diameter are both appreciable. With the shed hole diameter increased to 2.0 mm or higher, the discharge activity becomes very intensive. As a consequence, the heating of air makes some local arcs below the sheds floating around the rod. In this case, the local arcs may pass through the shed holes more easily even they are in an alternating arrangement. Therefore, the flashover voltage difference of two shed hole arrangements narrows.

B. THE INFLUENCE OF SHED HOLES ON THE DRY FLASHOVER AND WET FLASHOVER PERFORMANCE

Six type B (110 kV) insulators, namely from B-DW1 to B-DW6 as listed in Table 7, were used to study the influence of shed holes on dry flashover voltage V_{df} and wet flashover voltage V_{wf}. Specimen B-DW1 had no hole in its sheds while specimens from B-DW2 to B-DW4 had shed holes which were prepared in the straight-line arrangement. The shed holes of B-DW2 to B-DW6 started from the high voltage end and their proportions to the whole sheds were 1/3, 1/2, 100%, 100%, and 100%, respectively. For B-DW5, the holes at the small and medium sheds were in the straight-line arrangement while others at the big sheds were in the alternating arrangement. The shed hole diameter of B-DW2 to B-DW6 was 1.0 mm.

TABLE 7. Results of dry and wet flashover voltage tests of 110 kV composite insulator with shed hole diameter of 1.0 mm.

Specimen	V_{df} (kV)	β (%)	σ (%)	V_{wf} (kV)	β (%)	σ (%)	Notes
B-DW1	388	0.0	2.5	343	0.0	1.9	No shed hole
B-DW2	382	-1.6	7.1	344	0.3	4.4	1/3 shed holes
B-DW3	385	-0.8	5.9	342	-0.3	5.7	1/2 shed holes
B-DW4	389	0.3	4.6	336	-2.0	2.1	100% shed holes [a]
B-DW5	383	-1.3	1.8	339	-1.2	5.6	100% shed holes [b]
B-DW6	389	-0.3	3.9	340	-0.9	4.7	100% shed holes [c]

[a] All sheds were in straight-line arrangement.
[b] Small and medium sheds were in straight-line arrangement while big sheds were in alternating arrangement.
[c] Adjacent sheds were in alternating arrangement.

TABLE 8. Results of pollution-rain flashover tests of 500 kV composite insulator.

Shed Hole Diameter (mm)	ESDD = 0.05 mg/cm^2			ESDD = 0.10 mg/cm^2			Shed Hole Arrangement
	$U_{50\%}$ (KV)	β (%)	σ (%)	$U_{50\%}$ (KV)	β (%)	σ (%)	
0	378	0.0	3.6	347	0.0	4.5	No Shed Hole
1	344	-9.0	3.3	289	-16.7	1.4	Straight-line Arrangement
2	333	-11.9	4.2	278	-19.9	6.5	
3	324	-14.3	6.5	271	-21.9	2.6	
1	357	-5.6	1.9	311	-10.4	4.8	Alternating Arrangement
2	345	-8.7	6.8	283	-18.4	5.2	
3	340	-10.1	5.6	275	-20.7	3.8	

As listed in Table 7, with the presence of shed holes, the percentage of voltage drop of dry flashover voltage and wet flashover voltage are both not greater than 2.0%, regardless of the shed hole percentage and how the shed holes were arranged. The change of shed hole arrangement or the increase of shed holes do not lead to an appreciable decrease of flashover voltage. Therefore, the influence of shed holes on both dry flashover voltage and wet flashover voltage is negligible. According to the observation by the ultra-high-speed camera and the surface trace check after the test, the arc only passed through very few shed holes at the high voltage end and the ground end rather than the shed holes located in the middle of the insulator.

C. THE INFLUENCE OF SHED HOLES ON THE POLLUTION-RAIN FLASHOVER PERFORMANCE

In this part, type C (500 kV) insulators were tested and shed hole diameters of 1 mm, 2 mm, and 3 mm were investigated. The shed hole percentage was 2/3 and the holes were artificially made at the high voltage end.

The test results are listed in Table 8. As indicated in the table, the presence of shed holes can reduce the pollution-rain flashover voltage by −5.6% to −14.3% when ESDD is 0.05 mg/cm^2 and −10.4% to −21.9% when ESDD is

TABLE 9. Results of lightning impulse flashover tests of 110 kV composite insulator.

Insulator	$U_{50\%}$ (kV)	β (%)	σ (%)	Notes
B-L1	732	0.0%	2.9	No shed hole
B-L2	761	4.0%	5.1	Each shed has a hole
B-L3	696	-4.9%	4.3	Bare rod

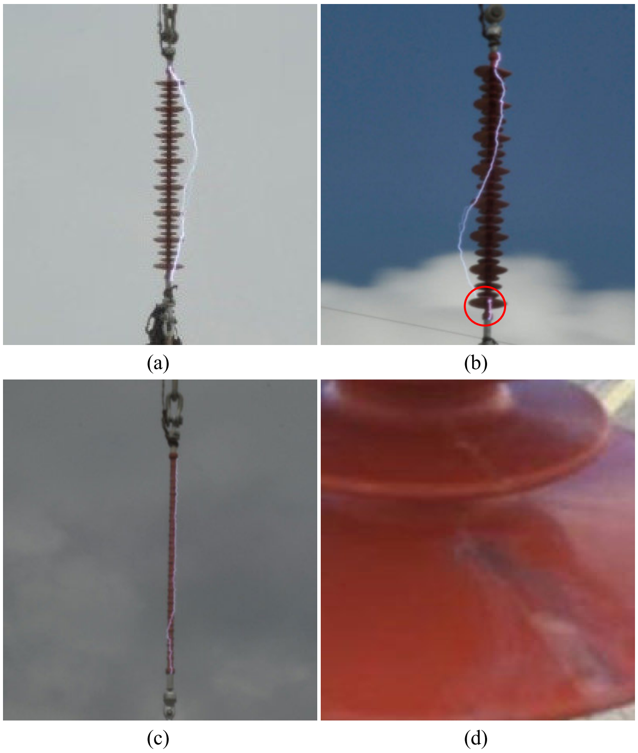


FIGURE 14. The lightning paths of three composite insulators. (a) B-I1; (b) B-I2; (c) B-I3; (d) Trace on the B-I2 insulator surface after a lightning impulse strike.

0.10 mg/cm^2, respectively. When the shed hole diameter is 1.0 mm, the flashover voltage is higher in the alternating arrangement than the straight-line arrangement. With the increase of shed hole diameter, the difference between two arrangements becomes insignificant. According to the data in Table 6 and Table 8, it can be calculated that the pollution-rain flashover voltage is 3.3% to 7.8% higher than that of pollution flashover when the ESDD is 0.1 mg/cm^2, which is consistent with the test results of composite post insulators in [24].

D. THE INFLUENCE OF SHED HOLES ON THE LIGHTNING IMPULSE PERFORMANCE

The lightning impulse tests were carried out at the outdoor laboratory in Kunming. Three new 110 kV type B composite insulators were selected as listed in Table 9. Among them, insulators B-L2 and B-L3 were treated before the tests as follows: shed holes with a diameter of 1.0 mm were made artificially at each shed of insulator B-L2 and all shed holes were in a straight-line arrangement while insulator B-L3 was trimmed to a bare rod with all sheds removed. The test results in Table 9 show that the presence of shed holes or even the sheds themselves has insignificant influence on the 50% lightning impulse flashover voltage of the insulator. Compared with insulator B-L1, the lightning impulse flashover voltage of insulator B-L3 which had no sheds is only 4.9% less. Figure 14 shows some arc paths at the time of flashover of three insulators.

According to the observations, the lightning path was always along the insulator rod of B-L3 which led to a shorter arc distance and a lower lightning impulse voltage. It should be noted that, insulator B-L2, although had shed holes, had a slightly higher lightning impulse flashover voltage than that of insulator B-L1. As the lightning passes through the hole at the first shed at the bottom of the insulator as shown in Figure 14(b), the lightning arc distance is even longer than that of insulator B-L1. After the lightning impulse test, a trace caused by the lightning impulse strike was left on the first shed surface at the bottom of the insulator, as displayed in Figure 14(d).

IV. CONCLUSION

To investigate the influence of shed holes on the electrical performance of composite insulators, a large number of experiments were conducted outdoor and in the chamber in this paper. According to the test results, the following conclusions can be drawn:

1) The pollution flashover voltage and pollution-rain flashover generally decrease with the increase of shed hole diameter, shed hole percentage and ESDD. Due to the presence of pollution, the arc were more likely to pass through the shed hole which could decrease the leakage distance dramatically.
2) It is worth noting that for the tested 35 kV composite insulators, the insulator can still withstand at the nominal voltage even the ESDD is very heavy at 0.15 mg/cm^2 and the shed hole diameter is 2.0 mm. After the pollution test, the diameter of shed holes is increased by 3% to 64%.
3) For the tested 500 kV composite insulators, when the shed diameter is 1.0 mm and ESDD is 0.1 mg/cm^2, the pollution-rain flashover voltage is 3.3% to 7.8% higher than that of the pollution flashover voltage. In both types of flashover tests, the flashover voltage with shed holes in alternating arrangement behaves better than that of the straight-line arrangement. However, with the increase of shed hole diameter, the discharge activity becomes more intensive. With local arcs floating around the rod, the flashover voltage difference of two shed hole arrangements is narrowed.
4) The presence of shed holes has negligible influence on the wet flashover voltage and dry flashover voltage of 110 kV composite insulator. The difference of flashover voltage is not greater than 2.0% for each type of flashover test, no matter how much the shed hole percentage is or how the shed holes are arranged. Under

these circumstances, the arc only passed through very few shed holes and the decrease of leakage distance was therefore limited. In addition, the influence of shed hole to the lightning impulse is also minor.

REFERENCES

[1] R. Hackam, "Outdoor HV composite polymeric insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 5, pp. 557–585, Oct. 1999.

[2] M. Farzaneh and W. A. Chisholm, *Insulators for Icing and Polluted Environments*. Hoboken, NJ, USA: Wiley, 2009.

[3] F. Yin, Xingliang, and M. Farzaneh, "Electrical performance of composite insulators under icing conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 6, pp. 2584–2593, Dec. 2014.

[4] J. Hu, X. Jiang, F. Yin, and Z. Zhang, "DC flashover performance of ice-covered composite insulators with parallel air gaps," *Energies*, vol. 8, no. 6, pp. 4983–4999, May 2015.

[5] X. Jiang, Y. Chao, Z. Zhang, J. Hu, and L. Shu, "DC flashover performance and effect of sheds configuration on polluted and ice–covered composite insulators at low atmospheric pressure," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 1, pp. 97–105, Feb. 2011.

[6] Y. Liu and B. Du, "Recurrent plot analysis of leakage current on flashover performance of rime-iced composite insulator," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 465–472, Apr. 2010.

[7] X. Liang and S. Li, "Looking to the future of composite insulators," in *Proc. INMR World Congr.*, Munich, Germany, 2015, pp. 18–21.

[8] X. Liang, Y. Gao, J. Wang, and S. Li, "Rapid development of silicone rubber composite insulator in China," *High Volt. Eng.*, vol. 42, no. 9, pp. 2888–2896, Sep. 2016.

[9] R. Tripathi, G. Grzybowski, and R. Ward, "Electrical degradation of 15 kv composite insulator under accelerated aging conditions," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Ottawa, OH, Canada, Jun. 2013, pp. 404–408.

[10] C. Fang, J. Wang, C. Hu, J. Zhou, P. Cao, and K. Wang, "Research on discharge phenomena of composite insulators during tracking wheel test and analysis on leakage current characteristic," *Power Syst. Technol.*, vol. 36, no. 4, pp. 242–246, 2012.

[11] G. Wu, X. Lin, W. Cai, R. Zhang, G. Xiao, and G. Gu, "The study of power frequency arc of composite insulators for overhead lines," *High Voltage Eng.*, vol. 28, no. 11, pp. 9–10, 2002.

[12] A. Bradwell, "Evaluation of shedded polymeric insulators for use on BR 25 kV overhead lines," in *Proc. 5th Int. Conf. Dielectr. Mater., Meas. Appl.*, Canterbury, U.K., 1988, pp. 361–365.

[13] *High-Voltage Test techniques—Part 1: General Definitions and Test Requirements*, document IEC 60060-1, 2010.

[14] *High-voltage Test techniques-Part 2: Measuring systems*, document IEC 60060-2, 2010.

[15] *IEEE Standard for High-Voltage Testing Techniques*, IEEE Standard 4-2013, 2013.

[16] F. Yin, X. Jiang, M. Farzaneh, and J. Hu, "Electrical performance of 330-kV composite insulators with different shed configurations under icing conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 6, pp. 3395–3404, Dec. 2015.

[17] X. Jiang, B. Dong, Z. Zhang, F. Yin, and L. Shu, "Effect of shed configuration on DC flashover performance of ice-covered 110 kV composite insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 3, pp. 699–705, Jun. 2013.

[18] M. Wei, K. Zhou, L. Song, H. Yu, D. Wang, and X. Yang, "Influence of altitude condition on the impulse and ac flashover voltages of insulators," *Insulators Surge Arresters*, vol. 1, pp. 11–15, Oct. 2015.

[19] *High-Voltage Test Techniques-Part 1: General Definitions and Test Requirements*, document IEC 60060-1: 2010.

[20] *High-Voltage Test Techniques-Part 2: Measuring Systems*, document IEC 60060-2, 2010.

[21] *Artificial Pollution Tests on High-Voltage Ceramic and Glass Insulators to Be Used on A.C. Systems*, document IEC 60507, 2013.

[22] X. Liu, Z. Zhang, K. Zheng, W. Li, and G. Yang, "Analysis of the pollution accumulation and pollution flashover performance of outdoor 500kV insulator string," in *Proc. Int. Conf. High Voltage Eng. Appl.*, Shanghai, China, Sep. 2012, pp. 250–253.

[23] *Artificial Pollution Tests on High-Voltage Ceramic and Glass Insulators to be Used on D.C. Systems*, document IEC TS 61245, 2015.

[24] F. Zhao, F. Zhang, Z. Guan, and L. Wang, "DC pollution flashover and rain flashover performance for composite post insulators at high altitudes," *J. Tsinghua Univ.*, vol. 49, no. 10, pp. 1581–1584, 2009.

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