Study on AC Flashover Performance for Different Types of Porcelain and Glass Insulators With Non-Uniform Pollution

Zhijin Zhang, Xiaohuan Liu, Xingliang Jiang, Jianlin Hu, and David Wenzhong Gao

***Abstract*—The ratio T/B of top to bottom surface salt deposit density (SDD) affects the ac pollution flashover performance of disk insulator strings. The ac pollution flashover stress was established for fifteen different combinations of SDD and T/B in a systematic study, making use of seven-unit suspension strings with six different disk profiles in this paper. Then a comparison was made of pollution performance for glass and porcelain disks with the same profile. The observed relation of ac flashover stress E_L to SDD and T/B followed an equation of the form $E_L = c \cdot \mathrm{SDD}^{-b} \cdot (1 - A \cdot \log(T/B))$. The values of c, b and A were fitted to test results for glass and porcelain disks of identical bottom-rib profile, and to four other bottom-rib and external-rib profiles. A reduction in the ratio T/B from 1/1 to 1/15 gave a median 26% ± 8% increase in flashover strength, corresponding to the calculated increase in overall pollution layer resistance. Extrapolation of results for the seven-unit strings to UHV dimensions suggests that some reduction in leakage distance can be accepted in areas where there is frequent natural washing of the top surfaces of disk insulators.**

***Index Terms*—Alternating current, correction factor, flashover voltage, insulator, salt deposit density, non-uniform contamination.**

I. Introduction

THE pollution on the surface of an insulator will pick up moisture under weather conditions that increase humidity such as fog, dew, and rain. Thus, its surface conductance and leakage current will increase greatly under an applied voltage, which may lead to the degradation of the surface electrical performance of polluted insulators and may even cause the occurrence of flashover.

Flash-over of insulators caused by pollution on their surfaces happens from time to time in China, and around the world. These flash-overs can lead to blackouts of the grid system. [1], [2]. According to the statistics, the number of power grid incidents caused by pollution flashover is second only to that by lightning. But the economic loss caused by pollution flashover is ten times larger than that by lightning [3]. Therefore, a lot of studies on the performance and mechanism of pollution flashover have been done in many countries as well as in China to prevent pollution flashover [1]–[33].

Experimental results show that the flashover voltage will decrease as pollution increases. Taking the pollution as an independent parameter, the mathematic relationship between the flashover voltage (U) and the equivalent salt deposit density (ESDD) can be expressed as follows:

$$U = a \cdot S^{-b} \tag{1}$$

where a is a constant related to the profile and material of insulator, atmospheric pressure and the type of voltage; S is the ESDD on the surface of insulator and b is the exponent characterizing the influence of pollution. Research indicates that the value of b is not constant as shown by the following studies:

The result of a study on dc pollution flashover performance of 14 different types of insulators showed that the value of b ranges from 0.3 to 0.33 and different insulators have different values of b [4].

According to the study on the dc pollution flashover performance of 12 different types of post type insulators, the values of b is not the same for different post type insulators and it ranges from 0.32 to 0.41 [5].

Based on the laboratory research on ac and dc pollution flashover performance, the value of b ranges from 0.17 to 0.30 for ac and 0.30–0.37 for dc [6]–[12].

Another experiment results showed that: with ac voltage applied, the values of porcelain and glass insulators is in the range of 0.22–0.31 and for composite insulators b is in the range of 0.19–0.27 [13]–[16].

The round-robin test on the dc pollution flashover of 5-unit insulator strings of standard, anti-polluting, post type insulators was made in Japan, Brazil, Sweden, Canada, America and Italy alternately and the results showed that the values of b is 0.33 for negative dc [17].

The study on the dc pollution flashover of various types of insulators showed that the b value of suspension insulators ranges from 0.32 to 0.33 and for post insulators it is in the range of 0.35–0.37 under the action of negative dc [18].

In order to reflect the practical operating situation of insulators more accurately, the pollution accumulation experiments of field operating insulators were studied in some countries. The pollution accumulation of ESDD from the top to bottom surface of insulators can be expressed as a ratio of T/B. Experiment results indicate that the pollution deposition on bottom surface

Manuscript received September 22, 2012; revised December 27, 2012; accepted January 25, 2013. Date of publication April 24, 2013; date of current version June 20, 2013. This work was supported by the National Natural Science Foundation of China (No. 5021005) and National Basic Research Program of China (973 Program) (No. 2009CB724503). Paper no. TPWRD-00989-2012.

Z. Zhang, X. Liu, X. Jiang, and J. Hu are with the State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400044, China (e-mail: zhangzhijin@cqu.edu.cn; 373798282@qq.com; xljiang@cqu.edu.cn; hujianlin@cqu.edu.cn).

D. W. Gao is with the Department of Electrical and Computer Engineering, University of Denver, Denver, CO 80208 USA (e-mail: gaowenz@yahoo.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2013.2245153

is more serious than that on top surface [19]–[23]. According to the operation experience of Chinese grids, the ratio (T/B) of porcelain and glass insulators is usually in the range of 1:5–1:10 and the maximum value is 1:20 [24].

The flash-over of an insulator has a direct relationship to the non-uniform distribution of pollution from the top to the bottom of the insulator. The pollution withstand voltage will increase by approximately 30% when the T/B ratio is lowered from 1:1 to 1:5 and increase by approximately 50% when the T/B ratio is lowered from 1:1 to 1:10 [25]. Based on the salt deposit density (SDD) of upper surface, the correction factor (K) for the influence on the dc pollution flashover voltage of porcelain and glass insulators is presented as follows [26]:

$$K = \frac{U_2}{U_1} = 1 - A \times \log\left(\frac{T}{B}\right) \tag{2}$$

where U_1 is the dc pollution flashover voltage of insulators with non-uniform pollution and U_2 is the dc pollution flashover voltage of insulators with uniform pollution; T/B is the ratio of the ESDD of top surface with respect to that of bottom surface; the value of coefficient A ranges from 0.29 to 0.47 with a mean value of 0.38. A study about the influence of non-uniform pollution distribution on the dc flashover voltage of composite insulators was carried out in [24]; and the result indicated that the value of A of composite insulators ranges from 0.141 to 0.156, which is lower than that of porcelain and glass insulators.

In [27], another research was done to study on the influence of non-uniform pollution distribution on ac flashover voltage of standard suspension insulators and found that the (2) is also applicable in ac case and the value of A was obtained as 0.31.

So far, much effective work on pollution flashover has been done around the world and the related results are applied in insulation coordination by designers. But the accident of pollution flashover of insulators has never disappeared in China since the 1990s. This means that the safe operation of Chinese power grid is still threatened by large scale pollution flashover [28].

The construction and development of UHV ac and dc transmission engineering projects is well under way in China and a number of large-tonnage porcelain and glass insulators will be used in some transmission lines. The external insulation design and selection in pollution regions is one of the most key technologies in the construction of Chinese UHV transmission engineering [29]. In this paper, the ac pollution flashover performance of different types of large diameter porcelain and glass insulators is studied to reveal the influence of non-uniform pollution distribution on pollution flashover performance and our research results will provide significant references for the external insulation design and selection of UHV ac transmission project.

II. Test Facilities, Specimens and Test Operating Procedure

A. Test Facilities

The artificial pollution tests were carried out in the multi-function artificial climate chamber in the State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University. The artificial climate chamber, with a diameter of 7.8 m and a height of 11.6 m, can simulate complex atmospheric environments such as fog, rain, ice and high altitude [6], [7].

The power was supplied by the YDTW-500-kV/2000-kVA pollution test transformer. The major technical parameters are as follows: rated capacity 2000 kVA, rated current 4 A and short-circuit impedance less than 6% under a rated voltage of 500 kV and the short circuit current 75 A at flashover. The tested circuit and the principle were detailed in [9].

TABLE I
Dimensions and Profiles of Insulators Tested

Types	Material	Dimensions (mm)			U_1	U_2
		D	H	L	(kV)	(kV)
A	glass	320	155	500	91	59
B	glass	400	195	635	94	63
C	glass	360	205	550	92	60
D	porcelain	400	195	635	112	72
E	porcelain	330	195	480	126	81
F	porcelain	400	195	635	118	65

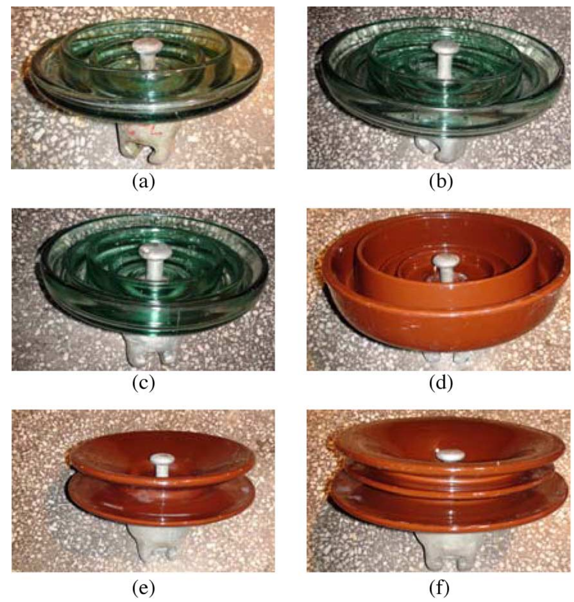


Fig. 1. Profiles of the insulators tested. (a) Type A; (b) Type B; (c) Type C; (d) Type D; (e) Type E; (f) Type F.

B. Test Specimens

The specimen insulators studied are six types of porcelain, glass insulators. Their profiles and dimensions as well as some of the parameters are shown in Table I and Fig. 1, in which D is the disc diameter, H is the configuration height, L is the creepage distance, U_1 is the dry flashover voltage and U_2 is the wet flashover voltage for a clean insulator.

C. Test Procedure

1) Preparation and Method of Pollution: Before the tests, all the samples were carefully cleaned so that all traces of dirt and grease were removed and the samples were let to dry naturally.

The insulators were polluted by quantitative coating using pasting method [33]. Sodium chloride and kieselguhr were used to simulate conductive and inert materials respectively. Firstly, the required amount of sodium chloride and kieselguhr were calculated and weighed according to the specified salt deposit density (SDD), non-soluble deposit density $(NSDD)$ and the surface areas of the specimens. The errors of the weight of sodium chloride and kieselguhr were less than $\pm 1\%$ and $\pm 10\%$, respectively. The ratio of SDD to $NSDD$ was 1/6 in all the tests. Then, sodium chloride and kieselguhr were mixed to slurry with appropriate volume of deionized water $(\sigma_{20} < 10\ \mu\mathrm{S/cm})$. In an hour after the preparing, the specimens were polluted by fully stirred suspension. After 24 hours of natural drying, the specimens were suspended into the climate chamber.

In order to produce the non-uniform pollution distribution on the top and the bottom surfaces of the insulator, both the average salt deposit density and the non-soluble density, which can be presented as SDD, should satisfy the condition during the artificial pollution produce process as follows:

$$SDD = \frac{SDD_B \cdot S_B + SDD_T \cdot S_T}{S_B + S_T} \tag{3}$$

$$T/B = \frac{SDD_T}{SDD_B} \tag{4}$$

where SDD_T represents the salt deposit density of the top surface with a surface area of S_T, SDD_B represents the salt deposit density of the bottom surface with a surface area of S_B. Therefore during the tests with various T/B, the total soluble materials on the insulator string are kept unchanged.

2) Arrangement: The minimum clearances between any part of the samples and any earthed objects met the requirements of [30], [31].

3) Wetting: The polluted insulators were wetted by steam fog. The steam fog was generated by a 1.5 t/h boiler; the nozzles were perpendicular to the axis of the test insulator; and the distance between them was greater than 3.5 m. The input rate of fog was $0.05 \pm 0.01\ \mathrm{kg/h \cdot m^3}$, and the temperature in the chamber was controlled between $30^\circ\mathrm{C}$ and $35^\circ\mathrm{C}$ through the refrigeration system and the atmospheric pressure is 98.6 kPa in all the experiments.

4) Evaluation: In this test, up and down method was adopted [6]–[11]. The insulator was subjected to at least 15 "valid" individual tests at a specified degree of contamination. The applied voltage level in each test was varied according to the up-and-down method and the voltage step was approximately 5% of the expected U_{50}.

The first "valid" individual test was selected as being the first one that yields a result different from the preceding ones. Only the individual test and at least 14 following individual tests were taken as useful tests to be considered to determine U_{50}. The U_{50} and relative standard deviation error (σ) could be calculated as follows:

$$U_{50} = \frac{(\sum(n_i V_i))}{N} \tag{5}$$

$$\sigma = \frac{\sqrt{\sum_{i=1}^{N}(V_i - U_{50})^2/(N-1)}}{U_{50}} \times 100\% \tag{6}$$

where V_i is an applied voltage level, n_i is the number of tests carried out at the same applied voltage V_i, and N is the total number of "valid" tests.

III. Experimental Results and Analysis

A. Experimental Results

The experiment on the pollution flashover performance of various types of insulator strings with 7 units was conducted as described above and the experimental results are presented in Table II.

The relative standard deviations of all experimental results is less than 7%, which means that the dispersion degree of pollution flashover performance of insulators acquired by this experiment method is very small.

The U_{50} of the various types of insulators decreases with the increase of their SDD. For example, when $T/B = 1$ and the value of SDD is 0.03 $\mathrm{mg/cm^2}$, 0.08 $\mathrm{mg/cm^2}$ and 0.20 $\mathrm{mg/cm^2}$, the U_{50} of A-type insulator string with 7 units is 152.1 kV, 112.3 kV and 82.1 kV, respectively. From the data above we can see that the U_{50} decreases by 26.2% and 46.0% respectively when the SDD increases from 0.03 $\mathrm{mg/cm^2}$ to 0.08 $\mathrm{mg/cm^2}$ and 0.20 $\mathrm{mg/cm^2}$ respectively.

Another factor that affects the U_{50} of insulator is its profile. The configuration height, disc diameter and leakage distance of B-type, D-type and F-type insulators are exactly the same, but their profiles are different. The U_{50} of B-type insulators is higher than that of D-type and F-type insulators under the same pollution condition. For example, the U_{50} of B-type, D-type and F-type insulator strings with 7 units is 132.2 kV, 125.1 kV and 114.8 kV respectively when $T/B = 1$ and $SDD = 0.08\ \mathrm{mg/cm^2}$. The data indicate that the U_{50} of B-type glass insulators is 5.4% and 13.2% higher than that of D-type and F-type porcelain insulators, respectively.

The non-uniformity of pollution of the upper and lower surface of insulators has significant influence on U_{50}. Moreover, the lower the T/B ratio, the greater the U_{50} of insulators. For example, the U_{50} of A-type insulators is 112.3 kV, 120.1 kV, 125.9 kV, 132.2 kV and 138.2 kV respectively when the value of SDD is 0.08 $\mathrm{mg/cm^2}$ and the T/B ratio is 1/1, 1/3, 1/5,1/ 8 and 15 respectively. The data indicate that there is an increase of 6.9%, 12.1%, 17.7% and 23.1% of the U_{50} of insulators respectively when the T/B ratio is decreased from 1/1 to 1/3, 1/5, 1/8 and 1/15.

B. Analysis on Differences of the AC Pollution Flashover Performance of Various Types of Insulators

The insulators' string length flashover gradient was defined as the ratio of U_{50} with respect to the length of insulator h, namely $E_h = \mathrm{U_{50}/h}$ and the insulators' creepage flashover gradient was defined as the ratio of $\mathrm{U_{50}}$ with respect to the creepage distance L, namely $E_L = \mathrm{U_{50}/L}$ [10]. According to the test results and the basic technical parameters of the insulators presented in Table I, the E_h and E_L of various types of polluted insulators are shown in Table III and IV.

The values of E_h of the tested insulators are in the range of 55–165 kV/m and they are dependant upon many factors, such as the profile and material of insulators, the pollution and the

TABLE II
TEST RESULTS OF VARIOUS TYPES OF INSULATOR STRINGS WITH 7 UNITS (kV)

Types	SDD mg/cm²	T/B									
		1/1		1/3		1/5		1/8		1/15	
		U_{50}	σ%	U_{50}	σ%	U_{50}	σ%	U_{50}	σ%	U_{50}	σ%
A	0.20	82.1	4.3	86.2	3.8	89.5	3.8	93.1	6.5	97.1	3.5
	0.08	112.3	3.8	120.1	2.6	125.9	3.6	132.2	5.9	138.2	4.5
	0.03	152.1	6.1	162.1	4.1	169.4	5.4	175.1	5.2	183.1	4.8
B	0.20	100.1	2.9	104.8	3.8	107.2	3.9	110.3	6.4	113.3	3.8
	0.08	132.2	4.6	141.5	3.1	147.3	5.0	150.8	4.8	152.5	4.5
	0.03	163.3	5.2	182.8	4.6	191.2	6.2	200.3	5.1	215.3	3.2
C	0.20	98.4	3.0	100.5	4.2	104.8	5.1	108.2	6.0	108.8	5.4
	0.08	127.7	4.3	133.5	4..8	141.5	4.3	151.4	4.2	162.1	5.1
	0.03	169.8	5.2	180.2	6.1	192.5	5.1	196.6	5.4	208.4	5.6
D	0.20	88.1	4.8	94.1	3.2	101.7	4.2	110.7	4.3	116.1	4.8
	0.08	125.1	4.9	129.8	4.3	137.8	3.9	148.5	5.7	155.9	6.1
	0.03	179.5	4.6	195.1	5.1	201.1	5.1	212.3	4.8	225.4	4.3
E	0.20	75.2	3.5	82.3	4.8	87.2	6.4	91.8	3.6	100.2	6.1
	0.08	105.5	6.3	113.7	4.6	125.1	3.8	129.6	3.8	145.3	5.0
	0.03	161.1	3.4	173.7	5.1	188.6	4.9	201.5	5.4	210.6	3.5
F	0.20	82.4	5.3	87.5	4.8	94.2	4.8	104.6	6.2	112.5	4.7
	0.08	114.8	4.5	122.9	5.5	138.1	6.2	147.2	6.5	152.8	3.8
	0.03	173.4	6.5	182.1	4.7	194.2	4.8	205.8	3.2	221.1	4.1

TABLE III
THE INSULATORS' STRING LENGTH FLASHOVER GRADIENT (EH) (kV/m)

Types	SDD mg/cm²	T/B				
		1/1	1/3	1/5	1/8	1/15
A	0.20	75.7	79.4	82.5	85.8	89.5
	0.08	103.5	110.7	116.0	121.8	127.4
	0.03	140.2	149.4	156.1	161.4	168.8
B	0.20	73.3	76.8	78.5	80.8	83.0
	0.08	96.8	103.7	107.9	110.5	111.7
	0.03	119.6	133.9	140.1	146.7	157.7
C	0.20	68.6	70.0	73.0	75.4	75.8
	0.08	89.0	93.0	98.6	105.5	113.0
	0.03	118.3	125.6	134.1	137.0	145.2
D	0.20	64.5	68.9	74.5	81.1	85.1
	0.08	91.6	95.1	101.0	108.8	114.2
	0.03	131.5	142.9	147.3	155.5	165.1
E	0.20	55.1	60.3	63.9	67.3	73.4
	0.08	77.3	83.3	91.6	94.9	106.4
	0.03	118.0	127.3	138.2	147.6	154.3
F	0.20	60.4	64.1	69.0	76.6	82.4
	0.08	84.1	90.0	101.2	107.8	111.9
	0.03	127.0	133.4	142.3	150.8	162.0

TABLE IV
THE CREEPAGE FLASHOVER GRADIENT (EL) OF VARIOUS TYPES OF INSULATORS (kV/m)

Types	SDD mg/cm²	T/B				
		1/1	1/3	1/5	1/8	1/15
A	0.20	23.5	24.6	25.6	26.6	27.7
	0.08	32.1	34.3	36.0	37.8	39.5
	0.03	43.5	46.3	48.4	50.0	52.3
B	0.20	22.5	23.6	24.1	24.8	25.5
	0.08	29.7	31.8	33.1	33.9	34.3
	0.03	36.7	41.1	43.0	45.1	48.4
C	0.20	25.6	26.1	27.2	28.1	28.3
	0.08	33.2	34.7	36.8	39.3	42.1
	0.03	44.1	46.8	50.0	51.1	54.1
D	0.20	19.8	21.2	22.9	24.9	26.1
	0.08	28.1	29.2	31.0	33.4	35.1
	0.03	40.4	43.9	45.2	47.8	50.7
E	0.20	22.4	24.5	26.0	27.3	29.8
	0.08	31.4	33.8	37.2	38.6	43.2
	0.03	47.9	51.7	56.1	60.0	62.7
F	0.20	18.5	19.7	21.2	23.5	25.3
	0.08	25.8	27.6	31.1	33.1	34.4
	0.03	39.0	41.0	43.7	46.3	49.7

non-uniformity of pollution distribution. Furthermore, the less pollution or the lower the T/B ratio, the larger the value of E_h. The value of E_h of A-type insulators is the highest and that of E-type insulators is the lowest under the same pollution condition. This means that the pollution flashover voltage of A-type insulator strings is the highest and that of E-type insulator strings is the lowest for the insulator strings with same structure height.

The E_L of the tested insulators are in the range of 18–63 kV/m and E_L value is also dependant upon the profile and material of insulators, the pollution, the T/B and so on. In addition, the less pollution or the greater the non-uniformity of pollution, the larger the value of E_L. Under the same pollution condition, the E_L values of A-type and C-type insulators are the highest while that of D-type and F-type insulators are the lowest. This indicates that the effective utilization rates of creepage distance of A-type and C-type insulators are higher than others.

It is now clear that the pollution flashover voltage of insulators with larger disc diameter and longer creepage distance are not always higher. For the various types of insulators that were tested, the anti-pollution property of unit structure height of the A-type insulators is the best and the effective utilization rate of creepage distance of the C-type insulators is the highest. Therefore, the ideal L/D value of insulator is in the range of 1.528–1.56.

IV. Influence of T/B on Pollution Flashover Voltage and Correction

A. Relationship Between Pollution Flashover Voltage and T/B

The T/B on the top and bottom surface of insulators affects its pollution flashover voltage and the relationship between them is shown in Fig. 2. From it we can see that the influence of the T/B on various types of insulators is different. For the 6 types of insulators that were tested, the effect of the T/B on E-type porcelain insulators is the greatest and that on A-type insulators is the smallest.

Equations (3) and (4) indicate that $SDD_{\mathrm{B}} > SDD$ and $SDD_{\mathrm{T}} < SDD$ when $T/B < 1$. For the insulators polluted by NaCl is even in the artificial pollution tests, their surface pollution layer conductivity $(SPLC)$ is directly proportional to the SDD when they are at the same temperature and saturated sufficiently [32]. In other words, the resistance of the top surface pollution layer will increase and that of the bottom surface pollution layer will decrease as the non-uniformity of pollution distribution increases.

The relationship among the form factor of insulator (f), the conductivity of pollution layer (γ), the surface conductance (G) and the resistance of pollution layer (R) is as follows:

$$\gamma = f \times G = \frac{1}{R} f. \tag{7}$$

The relationship between the form factor of insulator and its profile is as follows:

$$f = \int_0^L \frac{dl}{\pi D(l)} = \int_0^{L_T} \frac{dl}{\pi D(l)} + \int_{L_T}^{L} \frac{dl}{\pi D(l)} = f_T + f_B \tag{8}$$

where L is the creepage distance along the surface of insulator, L_T is the creepage distance along the top surface of insulator, dl is the increment of creepage distance, $D(l)$ is the diameter at distance dl, f_T and f_B is the form factor of the top and bottom surface of insulator respectively and f is the total form factor of insulator.

From (7) and (8), the following equation is obtained:

$$\gamma_{\mathrm{eq}} = \frac{f}{f_B/\gamma_B + f_T/\gamma_T} \tag{9}$$

where γ_{eq} is the equivalent conductivity of the whole insulator surface; γ_T is the conductivity of top surface and γ_B is that of bottom surface.

Because the $SPLC$ of insulator is directly proportional to its SDD, from (3) and (7)–(9), the ratio of the equivalent value of conductivity (k) of the whole insulator surface (γ_{eq}) with non-uniform pollution distribution to the surface conductivity (γ_1) with uniform pollution distribution can be expressed as follows:

$$k = \frac{\gamma_{eq}}{\gamma_1} = \frac{f \cdot SDD_T \cdot SDD_B}{SDD \cdot (f_B \cdot SDD_T + f_T \cdot SDD_B)}. \tag{10}$$

The related technical parameters of insulators calculated according to Table I and standard [33] are shown in Table V.

According to (3), (4), (10) and the parameters in Table V, the values of k of various types of insulators with non-uniform pollution distribution are obtained, and they are shown in Table VI.

From Table VI we can see that, the more uneven the pollution distribution on the top and bottom surface of insulator, the smaller the mean pollution surface conductivity along the whole surface of insulator. For example, the k of A-type insulator is 0.85, 0.67, 0.50 and 0.31 respectively when T/B decreases from 1 to 1/3, 1/5, 1/8 and 1/15, which means that the

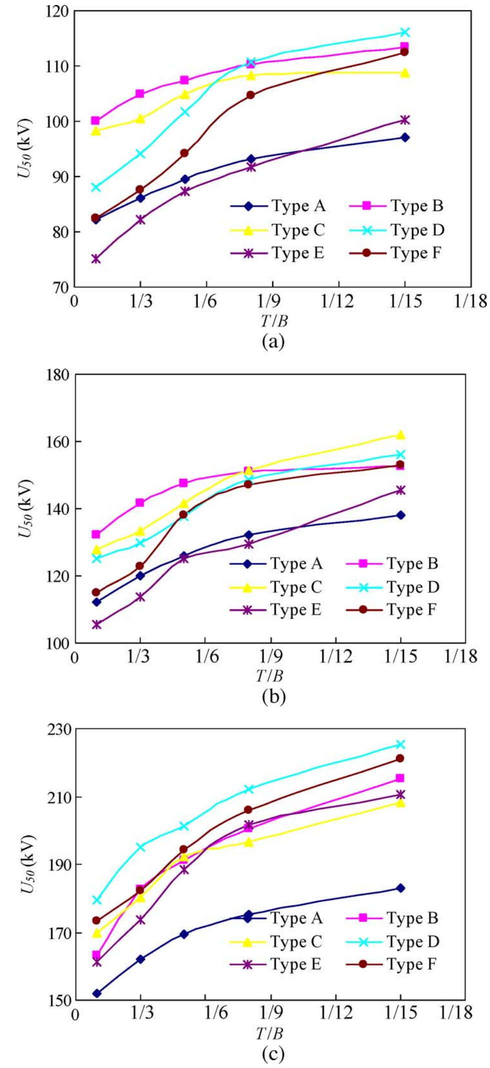


Fig. 2. Relationship between the pollution flashover voltage of insulators and T/B. (a) SDD $= 0.20\ \mathrm{mg/cm^2}$; (b) SDD $= 0.08\ \mathrm{mg/cm^2}$; (c) SDD $= 0.03\ \mathrm{mg/cm^2}$.

TABLE V
THE RELATED PARAMETERS OF DIFFERENT INSULATORS

Types	Parameters				
	f_B	f_T	f	S_B	S_T
A	0.619	0.226	0.845	2050	1124
B	0.845	0.255	1.070	2996	1820
C	0.535	0.225	0.760	2766	1499
D	0.796	0.217	1.013	3309	1989
E	0.495	0.332	0.827	1710	1810
F	0.926	0.460	1.386	2750	2860

TABLE VI
THE VALUE OF k OF INSULATORS WITH NON-UNIFORM POLLUTION

Types	T/B				
	1/1	1/3	1/5	1/8	1/15
A	1	0.85	0.67	0.50	0.31
B	1	0.89	0.72	0.55	0.35
C	1	0.82	0.64	0.21	0.29
D	1	0.93	0.77	0.60	0.38
E	1	0.84	0.65	0.48	0.29
F	1	0.91	0.73	0.54	0.34

effect of T/B change on the conductivity of top surface pollution layer is greater than that of bottom surface pollution layer; and the comprehensive function of it is to make the mean conductivity of the whole surface pollution layer increase with the increase of the ratio T/B.

Therefore, the leakage current may decrease with the decrease of the ratio T/B under the same applied voltage, which makes the formation of dry band difficult in the pollution layer on the insulator surface.

Moreover, the partial arc propagation criterion is [34]:

$$E_p > E_{arc} \tag{11}$$

where E_{p} is pollution voltage gradient and E_{arc} is arc voltage gradient which is calculated as [35]

$$E_{arc} = AI^{-n}. \tag{12}$$

According to the (12), the lower value of leakage current, the larger arc voltage gradient. It makes the partial arc propagation on the surface of polluted insulator difficult. So there is larger pollution flashover voltage under non-uniform pollution comparing with uniform pollution condition.

B. Insulators' Pollution Flashover Voltage Correction Under Non-Uniform Pollution

The results above indicate that the ac pollution flashover voltage of insulator is affected by its SDD and the T/B, so from (1) and (2), an equation is obtained as follows:

$$U_{50} = a \cdot SDD^{-b}\left[1 - A \cdot \log\left(\frac{T}{B}\right)\right]. \tag{13}$$

And define $c = a/L$, So

$$E_L = c \cdot SDD^{-b}\left[1 - A \cdot \log\left(\frac{T}{B}\right)\right]. \tag{14}$$

TABLE VII
RELATIVE ERRORS OF THE POLLUTION FLASHOVER VOLTAGE OF INSULATORS BETWEEN THE ACTUAL VALUES AND THE CALCULATED VALUES (%)

Types	SDD mg/cm^2	T/B				
		1/1	1/3	1/5	1/8	1/15
A	0.20	0.33	-3.13	-3.00	-2.26	-2.21
	0.08	1.86	0.31	1.38	3.00	3.27
	0.03	0.33	-1.59	-0.81	-0.73	-0.42
B	0.20	4.16	-0.28	-2.00	-2.69	-4.59
	0.08	4.39	2.14	2.19	1.04	-2.38
	0.03	-3.99	-1.76	-1.23	-0.09	2.57
C	0.20	4.43	-2.19	-1.84	-2.06	-6.05
	0.08	2.17	-2.20	-0.20	3.10	5.43
	0.03	0.28	-2.62	0.17	-1.14	0.31
D	0.20	0.78	-3.35	-0.13	4.21	3.81
	0.08	2.29	-4.78	-3.34	0.14	-0.17
	0.03	2.49	0.18	-1.39	-0.02	0.79
E	0.20	3.64	-0.36	-0.12	0.18	2.76
	0.08	0.36	-5.38	-1.24	-2.57	2.72
	0.03	2.83	-2.72	0.00	1.76	0.05
F	0.20	0.68	-5.80	-3.58	2.33	3.73
	0.08	-0.33	-6.02	0.56	2.32	0.24
	0.03	4.23	-3.16	-1.95	-0.73	0.60

Some mathematical methods and the fitting analysis based on (13) were adopted for the data in Table II, and a group of equations are obtained as follows:

$$E_L = \begin{cases} 97.0\cdot SDD^{-0.325}\left[1-0.181\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad A \\ 93.1\cdot SDD^{-0.301}\left[1-0.200\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad B \\ 103.8\cdot SDD^{-0.310}\left[1-0.193\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad C \\ 76.4\cdot SDD^{-0.366}\left[1-0.236\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad D \\ 78.5\cdot SDD^{-0.406}\left[1-0.293\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad E \\ 70.7\cdot SDD^{-0.373}\left[1-0.275\cdot\log\left(\frac{T}{B}\right)\right] & Type\quad F \end{cases} \tag{15}$$

The relative errors of the values of pollution flashover voltage of different insulators between the actual values and the values calculated by (15) are shown in Table VII.

Equation (15) and Table VII indicate that:

1) The relative errors of the ac pollution flashover voltage of insulators between the results calculated by (13) and the actual values are within 6%; so it is acceptable to express the relationship between the pollution and T/B of insulators and the ac pollution flashover voltage of insulators by (13), which is similar to the dc experimental results.
2) The effects of the T/B on the ac pollution flashover voltage of various types of insulators are different. The value of A of the 6 various types of insulators is 0.181, 0.200, 0.193, 0.236, 0.293 and 0.275, respectively, but they are all smaller than that of the porcelain insulators with dc voltage applied [24], [26].

V. CONCLUSIONS

From the above tests and analysis, some conclusions are obtained as follows:

1) The ac pollution flashover voltage (U_f) of large tonnage porcelain and glass insulators are influenced by their surface SDD and T/B; and the effects of the SDD and T/B on various types of insulators are different.
2) The relationship among the ac pollution flashover stress (E_L), SDD and T/B of large tonnage porcelain and glass insulators is shown as follows:

$$E_L = c \cdot SDD^{-b}\left[1 - A \cdot \log\left(\frac{T}{B}\right)\right].$$

For the 6 various types of porcelain and glass insulators that were tested in this paper, the value of b is in the range of 0.30–0.41 and the value of A is in the range of 0.18–0.30.
3) The insulator with bigger disc diameter and longer creepage distance does not always have a higher ac pollution flashover voltage. It is found that the insulators tested in this paper with L/D values between 1.528 and 1.563 have better anti-pollution properties of unit structure height and higher effective utilization rates of creepage distance.
4) The more uneven the pollution distribution on the top and bottom surface of insulators, the smaller the mean pollution surface conductivity along the whole surface of insulators.

Acknowledgment

The authors thank all members of the external insulation research team with the College of Electrical Engineering, Chongqing University, for their hard work to obtain the experimental data in this paper.

References

[1] M. Leclerc, R. P. Bouchard, Y. Gervais, and D. Mukhedkar, "Wetting processes on a contaminated insulator surface," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 5, pp. 1005–1011, May 1982.
[2] R Zhang and J. Zheng, "Progress in outdoor insulation research in China," *IEEE Trans. Elect. Insul.*, vol. 25, no. 6, pp. 1125–1137, Dec. 1990.
[3] Z. Zhang, X. Jiang, Y. Cao, C. Sun, and J. Hu, "Influence of low atmospheric pressure on AC pollution flashover performance of various types insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 425–433, Apr. 2010.
[4] R. Sundararajan, "Effect of insulator profiles on dc flashover voltage under polluted conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 1, no. 1, pp. 124–132, Feb. 1994.
[5] A. C. Baker, L. E. Zaffanella, L. D. Anzivino, H. M. Schneider, and J. H. Moran, "Contamination performance of HVDC station post insulators," *IEEE Trans. Power Del.*, vol. 3, no. 4, pp. 1968–1975, Oct. 1988.
[6] X. Jiang, J. Yuan, Z. Zhang, J. Hu, and L. Shu, "Study on pollution flashover performance of short samples of composite insulators intended for ±800 kV UHV DC," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 5, pp. 1192–1200, Oct. 2007.
[7] X. Jiang, J. Yuan, L. Shu, Z. Zhang, J. Hu, and F. Mao, "Comparison of DC pollution flashover performances of various types of porcelain, glass, and composite insulators," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 1183–1190, Apr. 2008.
[8] X. Jiang, J. Yuan, L. Shu, Z. Zhang, and Q. Hu, "Study on ac pollution flashover performance of composite insulators at high altitude sites of 2800–4500 m," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 1, pp. 123–132, Feb. 2009.
[9] X. Jiang, J. Yuan, L. Shu, Z. Zhang, J. Hu, and C. Sun, "Study on AC artificial-contaminated flashover performance of various types of insulators," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2567–2574, Oct. 2007.
[10] Z. Zhang, X. Jiang, Y. Cao, L. Chen, C. Sun, and J. Hu, "Study on DC pollution flashover performance of various types of long string insulators under low atmospheric pressure conditions," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2132–2142, Oct. 2010.
[11] Z. Zhang, X. Jiang, C. Sun, J. Hu, and H. Huang, "Study of the influence of test methods on DC pollution flashover voltage of insulator strings and its flashover process," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 6, pp. 1787–1795, Dec. 2010.
[12] X. Jiang, L. Chen, Z. Zhang, C. Sun, L. Shu, and M. T. Mazir, "Effect of arc-levitating from polluted insulators' surface in the low air pressure on its DC flashover performance," *IET Gen., Transm. Distrib.*, vol. 5, no. 7, pp. 729–734, 2011.
[13] Z. C. Guan and R. Y. Zhang, "Calculation of dc and ac flashover voltage of polluted insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 723–729, Aug. 1990.
[14] F. Zhang, X. Wang, L. Wang, Z. Guan, H. Wen, R. Li, and Y. Ma, "Effect of arcing on DC flashover performance of contaminated porcelain insulators for various suspension patterns at high altitudes," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 783–791, Jun. 2008.
[15] R. Zhang, D. Zhu, and X. Wang, "Configuration effect on dc flashover on polluted insulators," *IEEE Trans. Elect. Insul.*, vol. 25, no. 3, pp. 575–581, Jun. 1990.
[16] X. Liang, S. Wang, J. Fan, and Z. Guan, "Development of composite insulators in China," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 5, pp. 586–593, Oct. 1999.
[17] K. Naito and H. M. Schneider, "Round-robin artificial contamination test on high voltage DC insulators," *IEEE Trans. Power Del.*, vol. 10, no. 3, pp. 1438–1442, Jul. 1995.
[18] F. V. Topalis, I. F. Gonos, and I. A. Stathopulos, "Dielectric behavior of polluted porcelain insulators," *Proc. Inst. Elect. Eng., Gen. Transm. Distrib.*, vol. 148, no. 4, pp. 269–274, 2001.
[19] K. Naito, Y. Hasegawa, and T. Imakoma, "Improvement of the DC voltage insulation efficiency of suspension insulators under contaminated conditions," *IEEE Trans. Elect. Insul.*, vol. 23, no. 6, pp. 1025–1032, Dec. 1988.
[20] M. A. Douar, A. Mekhaldi, and M. C. Bouzidi, "Flashover process and frequency analysis of the leakage current on insulator model under non-uniform pollution conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 4, pp. 1284–1297, Aug. 2010.
[21] S. Chakravorti and P. K. Mukherjee, "Power frequency and impulse field calculation around a HV insulator with uniform or non-uniform surface pollution," *IEEE Trans. Elect. Insul.*, vol. 28, no. 1, pp. 43–53, Feb. 1993.
[22] M. A. El Koshairy and F. A. M. Rizk, "Comportement des Isolateurs des Lignes de Transport de Très Haute...Tension Dans les Conditions Désertiques," CIGRE, Paris, France, Rapport 33-05, 1970.
[23] M. Teguar, A. Mekhaldi, A. Bouhafs, and A. Boubakeur, "Comportement des surfaces Isolantes Sous pollution non-uniforme," in *Proc. 2nd Int. Conf. Elect. Power Eng., buletinul Institutului polytechnic Din Iasi by Universitatea Tehica "GH,Asachi", Tome XLVIII (LII)*, 2002, pp. 239–244.
[24] X. Jiang, S. Wang, Z. Zhang, J. Hu, and Q. Hu, "Investigation of Flashover Voltage and Non-uniform Pollution Correction Coefficient of Short Samples of Composite Insulator Intended for ±800 kV UHVDC," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 1, pp. 71–80, Feb. 2010.
[25] H. Ye, J. Zhang, Y. Ji, W. Sun, K. Kondo, and T. Imakoma, "Contamination accumulation and withstand voltage characteristics of various types of insulators," in *Proc. IEEE 7th Int. Conf. Properties Appl. Dielectr. Mater.*, Nagoya, Japan, 2003, pp. 1019–1023.
[26] EPRI, "HVDC transmission line insulation performance," USA, Rep. no. EL24618, 1986.
[27] W. Sima, T. Yuan, Q. Yang, K. Xu, and C. Sun, "Effect of non-uniform pollution on the withstand characteristics of extra high voltage (EHV) suspension ceramic insulator string," *IET Gen., Transm. Distrib.*, vol. 4, no. 3, pp. 445–455, 2010.
[28] Z. Zhang, X. Jiang, and C. Sun, "Present situation and prospect of research on flashover characteristics of polluted insulators," (in Chinese) *Power Syst. Technol.*, vol. 30, no. 2, pp. 35–40, 2006.
[29] J. Hu, C. Sun, X. Jiang, Z. Zhang, and L. Shu, "Flashover performance of pre-contaminated and ice-covered composite insulators to be used in 1000 kV UHV AC transmission lines," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 6, pp. 1347–1356, Dec. 2007.
[30] *Artificial Pollution Tests on High Voltage Insulators to be Used on ac Systems* (in Chinese), GB/T 4585-2004, 2004.
[31] *Artificial Pollution Tests on High Voltage Insulators to be Used on ac Systems*, IEC 60507-1991, 1991.

[32] C. Sun, L. Shu, and W. Sima, *Atmospheric Environment and Outdoor Insulation* (in Chinese). Beijing, China: Chinese Power Press, 2002.

[33] *Artificial Pollution Tests on High-Voltage Insulators to be Used on ac Systems Solid-Layer Method* (in Chinese), GB/T 4585.2-91, 1991.

[34] R. Sundararajan and R. S. Gorur, “Dynamic arc modeling of pollution flashover of insulators under DC voltage,” *IEEE Trans. Elect. Insul.*, vol. 28, no. 2, pp. 209–219, Apr. 1993.

[35] F. A. M. Rizk, “Mathematical models for pollution flashover,” *Electra*, vol. 78, pp. 71–103, 1981.

Xingliang Jiang was born in Hunan Province, China, on July 31, 1961. He received the M.Sc. and Ph.D. degrees from Chongqing University, Chonqing, China, in 1988 and 1997, respectively.

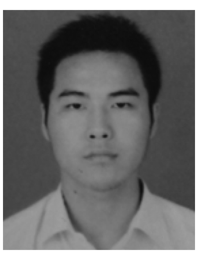
His employment experiences include the Shaoyang Glass Plant, Shaoyang, Hunan Province; Wuhan High Voltage Research Institute, Wuhan, Hubei Province; and College of Electrical Engineering, Chongqing University, Chongqing, China. His special fields of interest include high voltage external insulation and transmission line icing and protection.

Zhijin Zhang was born in Fujian Province, China, in July 1976. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Chongqing University, Chonqing, China, in 1999, 2002, and 2007, respectively.

He is a Professor of the College of Electrical Engineering, Chongqing University. He is the author or coauthor of several technical papers. His main research interests include high voltage, external insulation, numerical modeling, and simulation.

Jianlin Hu was born in Hubei Province, China, in January 1978. He received the B.Sc. and M.Sc. degrees in electrical engineering from Chongqing University, Chongqing, China, in 2001 and 2003, respectively, and is currently pursuing the Ph.D. degree at the College of Electrical Engineering, Chongqing University.

He has been a Teacher in the College of Electrical Engineering, Chongqing University since 2003. His main research interests include high voltage external insulation.



Xiaohuan Liu was born in Hubei Province, China, in 1984. He received the B.Sc. degree from Hubei University of Technology, Hubei, China, in 2006 and is currently pursuing the M.Sc. degree at Chongqing University, Chongqing, China.

His main research interests include high voltage and external insulation.

David Wenzhong Gao received the M.S. and Ph.D. degrees in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 1999 and 2002, respectively.

His current teaching and research interests include renewable energy and distributed generation, power delivery, power-electronics applications, power system protection, power system restructuring, and hybrid electric propulsion systems.