

Impact of Hydrophobicity on Wetting Characteristics of Composite Insulators

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ABSTRACT To perfect the wetting mechanism of hydrophobic insulators, it is urgent to explore the impact of hydrophobicity on wetting characteristics of the pollution layer of composite insulators. In this article, the wetting test of the hydrophobic pollution layer was carried out in artificial hot fog. The local surface conductivity of the pollution layer with different hydrophobicity were measured. The test results show that the local surface conductivities of different hydrophobic pollution layers are obviously different at the same wetting time. For researching the regularity of wetting process in greater detail, three characteristic quantities were proposed to represent the wetting characteristics. They are the duration of local surface conductivity close to zero (DLSCCZ), the saturated wetting time (SWT) and the maximum value of local surface conductivity (MVLSC). With the enhancement of hydrophobicity of the pollution layer, DLSCCZ and SWT increase, while MVLSC and the growth velocity of local surface conductivity both decrease.

INDEX TERMS Composite insulators, hydrophobicity, local surface conductivity, wetting characteristics, pollution layers.

I. INTRODUCTION

Pollution on insulator surface is hardly conductive in the dry state. When the pollution is wetted, the soluble salt in the pollution layer will be dissolved into conductive medium, which increases the risk of insulator flashover accident [1]–[4]. The insulator is the key equipment of transmission system, and its operation safety is related to the stable operation of power grid [5]. It is of great significance to research the wetting characteristics of the pollution on insulator surface for mastering its wetting mechanism.

Composite insulators have excellent performance in anti-pollution flashover due to the unique hydrophobicity, hydrophobicity recovery and hydrophobicity migration characteristics [6]–[8]. Hence, composite insulators have been widely used in power grid [9]. According to statistics, the consumption of transmission line composite insulators in China has reached 9 million by 2016. Compared with hydrophilic porcelain and glass insulators, the flashover voltage of hydrophobic composite insulators is obviously higher [10]–[12]. However, due to the wetness of pollution layers

caused by high humidity weather such as fog and so on, flashover of composite insulators still exists [13].

Since 1970s, international attention has been paid to the wetness problem of insulator pollution layers. Based on thermodynamic theory and experimental study, Karady and Leclerc *et al.* pointed out that there were four kinds of wetting ways of pollution layer [14], [15]. They are condensation, droplet collision, water molecule diffusion and hygroscopicity of pollution. The first two are the dominant wetting ways. Subsequently, the characterization methods of wetting degree of insulator pollution layers were proposed successively, namely leakage current method, conductivity method and phase angle difference method. Zhang *et al.* put forward that leakage current could characterize the wetting degree of the pollution on insulator surface well. When the leakage current reaches its maximum, the pollution is saturated wetting [16]. Cao *et al.* suggested that the conductivity of silicone rubber specimens was positively correlated with the water content of the pollution on insulator surface [17]. Yang *et al.* proposed the phase angle difference method to characterize the partial wetting degree of insulators [18]. Scholars have done lots of research on wetting of hydrophilic porcelain and glass insulators. The influence characteristics of pollution deposit

density, temperature, humidity, temperature difference, vapor fog velocity, pollution composition, types and materials of insulators on water accumulation, wetting speed and wetting degree of hydrophilic pollution layers have been obtained [16]–[24]. Moreover, the positive correlation between the wetting degree of pollution layer and the flashover voltage of glass insulators was demonstrated [18]. Wetting characteristics of hydrophilic insulators have been quite perfect, but little research has been done on hydrophobic insulators.

Some scholars then began to focus to the moisture problem of composite insulators. Zhang *et al.* presented that composite insulator had a lower wetting velocity than glass and porcelain insulators when they were all dried for 24 hours [16]. Yang *et al.* further indicated that wetting velocity of composite insulator with HC7 was still less than that of hydrophilic porcelain and glass insulators [24]. These researches focus on the comparison of the wetting speed between composite insulator and hydrophilic insulator, but pay less attention to the influence of hydrophobicity on wetting characteristics. The presence of hydrophobicity makes pollution on insulator surface have a strong repellency to moisture. Moisture on insulator surface is easy to appear as discrete water droplets instead of a continuous water film. Hydrophobicity makes the wetting process of hydrophobic composite insulators more complicated in theory. Cao *et al.* divides the hydrophobicity of pollution layers on silicone rubber test specimens into four regions through contact angle. The water accumulation and surface conductivity of the four hydrophobic pollution layers within 16 minutes of wetting were then studied [25]. While the test specimen of this study is rubber specimen rather than an entire insulator. And the duration of wetness in the study was too short. The study on the full wetting period of the composite insulator needs to be further explored.

In this article, wetting characteristics of hydrophobic pollution layer on insulator surface during whole wetting process was detected, local surface conductivity γ_{20} of the pollution layers on composite insulator surface were measured. In order to explore the wetting characteristics of seven Hydrophobicity Classes (HCs) of pollution layers systematically, three characteristic quantities were extracted to represent the wetting characteristics. They are duration of local surface conductivity close to zero (DLSCCZ), the saturated wetting time (SWT) and the maximum value of local surface conductivity (MVLSC). The influence mechanism of hydrophobicity on the wetting of pollution on insulators was then analyzed.

II. TEST FACILITIES, SPECIMENS AND METHODS

A. TEST FACILITIES

Using the self-made phase angle difference wetting degree detection system [18], the wetting characteristics of the pollution layer on composite insulator surface were explored by adding hot fog into the artificial climate tank. The wetting degree detection system was shown in Figure 1.

The wetting degree detection system is mainly composed of closed artificial climate tank, steam boiler, phase angle difference detection device, oscilloscope and so on. The enclosed artificial climate tank is 3.6 m in diameter and

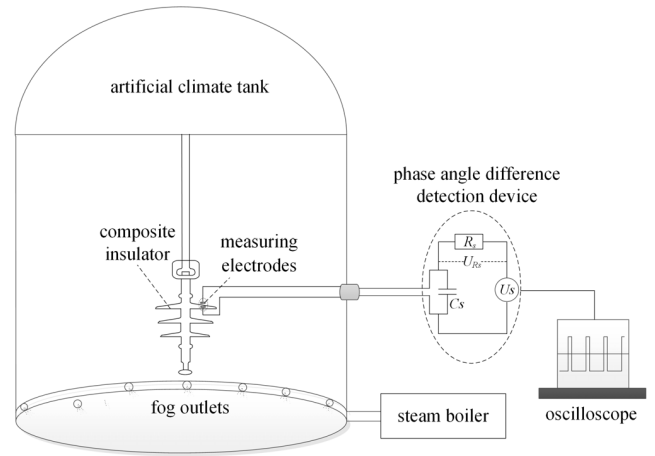


FIGURE 1. The wetting degree detection system.

4.2 m in height. The climate tank is connected with the steam boiler, and there is a row of fog outlets around the bottom for the output of steam hot fog. The size of the fog particles is 20-50 μm .

B. PRINCIPLE OF PHASE ANGLE DIFFERENCE DETECTION

Phase angle difference value θ can be measured from the phase angle difference detection device in Figure 1. The resistance R_x (in Ω) of the pollution layer deduced from θ is as follows:

$$R_x = \frac{\frac{1}{\omega C_s} + \sqrt{\left(\frac{1}{\omega C_s}\right)^2 + \frac{4R_s}{\omega C_s \tan(\theta)} - 4R_s^2}}{2 \left[\frac{1}{\tan(\theta)} - R_s \omega C_s \right]} \quad (1)$$

where ω is the angular frequency of the power supply, rad/s; C_s is the capacitance parallel to both sides of the measuring electrodes, nF; R_s is the sampling resistance, k Ω .

The temperature and the shape of measuring electrodes have an effect on the surface conductivity. Therefore, the conductivity of the polluted area on the insulator surface is:

$$\gamma_{20} = K_t K_f / R_x \quad (2)$$

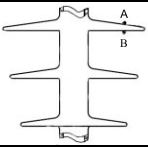
where γ_{20} is the surface conductivity at 20 $^\circ\text{C}$, K_t is the temperature compensation coefficient converted to 20 $^\circ\text{C}$, and K_f is the shape coefficient of the electrodes. For the rectangular electrode used in this article, the shape coefficient $K_f = W/L$, W represents the distance between copper electrodes, L represents the length of copper electrodes.

C. TEST SPECIMENS

The FXBW-10/70 composite insulator with simple structure was selected as test specimens. The schematic diagram and detailed parameters of the specimens are shown in Table 1, where L (in millimeters) is the creepage distance, S (in square centimeter) is the surface area of the test insulator.

Swedish Transmission Research Institution [26] proposed the spray method to divide the hydrophobicity into seven classes: HC1-HC7. The HC level is judged by the shape of droplets and the percentage part of the wetted

TABLE 1. Technical parameters of the test insulator.

Schematic diagram	Type	L (mm)	S (cm ²)
	FXBW-10/70	350	600.55

surface. HC1 corresponds to the most hydrophobic surface and HC7 corresponds to the most hydrophilic surface. The test procedure of the spray method is as follows: Squeeze the spray bottle once a second from a distance of 25 cm. Spray 0.7-1.0 ml water each time for 25 times. And the angle between the test insulators and the horizontal plane is 20-30°. According to the wetting appearance and the criteria for the HC, the HC level will be given within 10 s after the spraying has been accomplished [27].

The hydrophobicity of the test specimens was checked before the wetting test. The polluted composite insulators were dried for over 72 h under stationary temperature and relative humidity (30 °C±2 °C, 45% RH~50% RH). Then the polluted insulator whose hydrophobicity is below HC1 level (Only discrete droplets are formed. The shape when viewed perpendicular to the surface is practically circular [27].) was eliminated.

Two pairs of electrodes, denoted A and B, were installed at the upper shed and lower sheds in the creepage direction before the application of artificial pollution, as shown in Table 1. The measuring electrodes are copper conductive adhesive with a width of 15 mm and a spacing of 6 mm.

D. POLLUTING METHOD

Quantitative coating with pasting method was adopted to pollute the insulator surface [28], [29]. The polluting operations were as follows:

(1) Before the tests, all insulators were cleaned by pure water so that traces of dirt, grease and other adhesives were weeded out. These insulators were then placed in a ventilated and dry place.

(2) In this article, the equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) are 0.2 mg/cm² and 1.0 mg/cm², respectively. Sodium chloride (NaCl) and kieselguhr were used to simulate conductive and inert materials. The purity of NaCl used in experiments is not less than 99.5%.

(3) High-precision analytical balance with accuracy of 0.1 mg was used to weigh the required NaCl and kieselguhr. The quality error of NaCl is less than ±1% and that of kieselguhr is less than ±10%. NaCl and kieselguhr were put into a small beaker. The contamination was dissolved by injecting about 1 ml distilled water into beaker slowly with a rubber head dropper. A small brush was used to mix the contamination solution thoroughly and brush the contamination solution on the insulator surfaces uniformly. The first contamination solution used for dipping brushes in the test was abandoned.

E. WETTING DEGREE DETECTION METHOD

(1) The insulator was hung at a fixed position in the artificial climate tank. The steam boiler was then opened, and the steam hot fog was introduced into the climate tank. After about 1 minute, the artificial climate tank begins to fill with steam fog. The pollution layer was wetted by the steam fog with a constant input velocity.

(2) During the wetting process, local surface conductivity γ_{20} was recorded every 30 seconds. During the period when γ_{20} changes dramatically, γ_{20} was recorded every 10 seconds. The wetting test of pollution layer on insulator surface was repeat at least three times under the same working condition.

F. HYDROPHOBICITY MIGRATION TEST

By controlling the migration time of the polluted composite insulators, the pollution layer on the insulator surface with different hydrophobicity was obtained. The process of the hydrophobicity migration test is as follows:

(1) The polluted insulators were dried for different time in a constant temperature and humidity box. The temperature and relative humidity were 30 °C±2 °C and 45% RH~50% RH, respectively.

(2) According to the spray method [27], the spray experiment was carried out on the polluted insulator. Then the wetting appearance of the pollution layer were recorded. The hydrophobicity migration test was repeated five times in each migration time.

(3) In addition, we usually set up two other reference composite insulators. Through carrying out water spray test on the pollution layer of the two reference composite insulators, the HC level of the pollution layer of the test composite insulator can be further confirmed. The migration time of the test insulator is the same as that of the two reference insulators.

III. RESULTS AND ANALYSIS

A. IMPACT OF MIGRATION TIME ON HYDROPHOBICITY

The wetting appearance of the polluted insulators with different migration time is shown in Figure 2. According to the criteria for determination of the HC [27], the relationship between the HC level of the pollution layer on the composite insulator surface and the migration time is shown in Table 2.

B. IMPACT OF HYDROPHOBICITY ON WETTING

The wetting process of the upper and lower pollution layer on the polluted composite insulators was detected. For the composite insulator with different HCs, the local surface conductivity γ_{20} varying with time are plotted in Figure 3.

From inspection of Figure 3, the following conclusions can be drawn.

(1) The local surface conductivities of different hydrophobic pollution layers are obviously different at the same wetting time.

In order to explain the wetting characteristics of the pollution layer theoretically, the driving force model of the pollution layer on composite insulators was put forward.

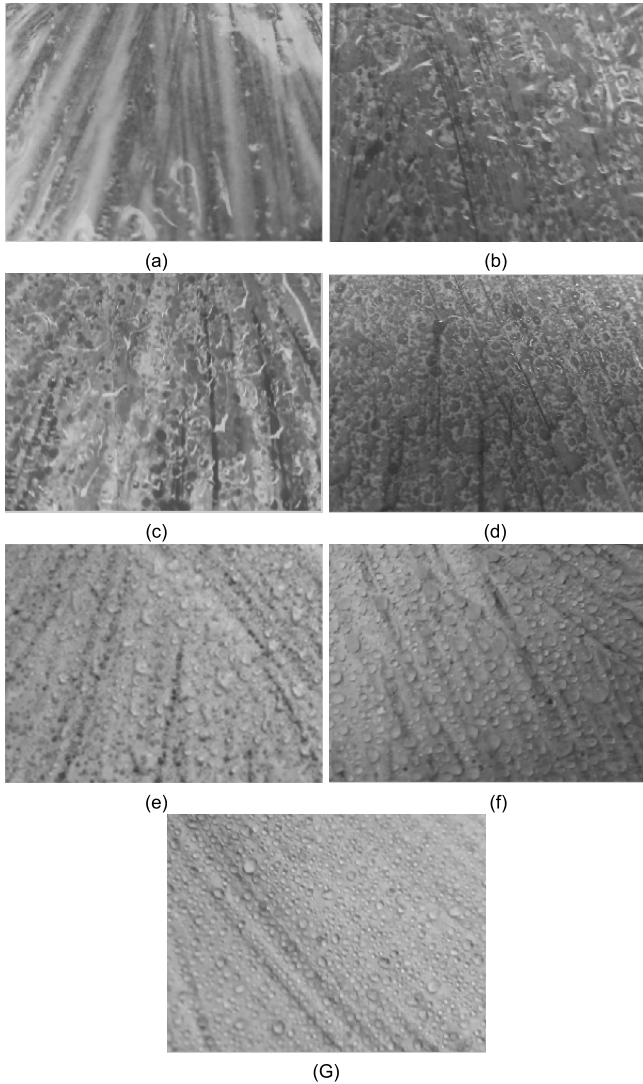


FIGURE 2. The wetting appearance under different migration time (a) 0.5h. (b) 1-2h. (c) 4-6h. (d) 8-12h. (e) 18-24h. (f) 48h. (g) ≥ 72h.

TABLE 2. Relation between HC level of the pollution layer and migration time.

Migration time	0.5h	1-2h	4-6h	8-12h	18-24h	48h	≥72h
HC	7	6	5	4	3	2	1

The wetting of the pollution layer is adhesive wetting, and the driving force F of the adhesive wetting process is:

$$F = \gamma_{sg} - \gamma_{sl} + \gamma_{lg} \quad (3)$$

where γ_{sg}, γ_{lg} and γ_{sl} are the interfacial tension for solid-gas, liquid-gas and solid-liquid respectively, with the unit of N/m.

The interfacial tension should satisfy Young's equation [30]:

$$\gamma_{sg} = \gamma_{sl} + \gamma_{lg} \cos \theta \quad (4)$$

Therefore, the driving force becomes

$$F = \gamma_{lg}(1 + \cos \theta) \quad (5)$$

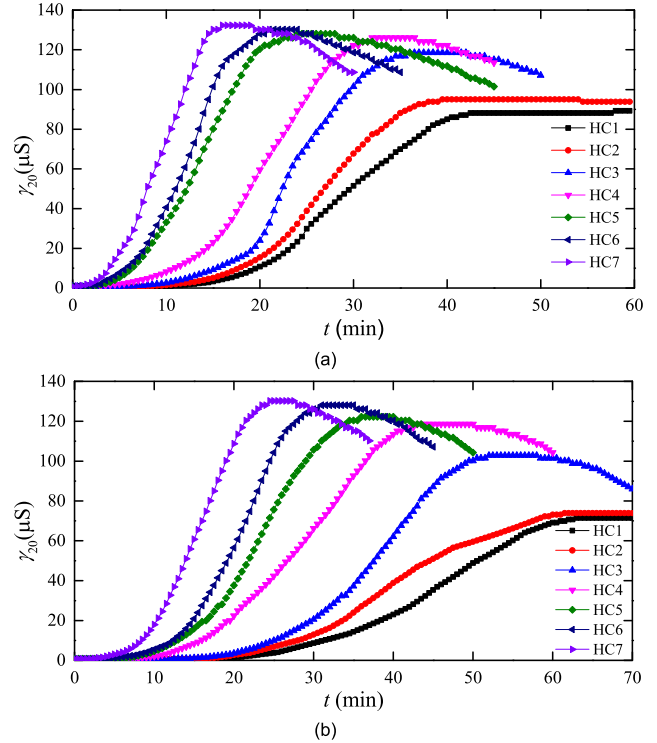


FIGURE 3. Local surface conductivity γ_{20} variation curves of polluted composite insulators with different HCs. (a) upper surface. (b) lower surface.

where, θ is the contact angle, and θ is between $0^\circ\text{C} - 180^\circ\text{C}$. The liquid will wet the solid easier when the driving force F increase.

With the improvement of HC level from 7 to 1, the contact angle θ gradually increases [27] and driving force F decreases. Different driving forces F make the dissolution rate of conductive medium from salt be different. Therefore, the local surface conductivity γ_{20} of different hydrophobic pollution layers is diverse although the wetting time is same.

(2) When the pollution layer is dried, the local surface conductivities γ_{20} of composite insulators with different HCs are all close to 0. It indicates that composite insulators under dry condition have similar good insulation ability even though their surface hydrophobicity is different.

(3) As the wetting progressed, the overall change trend of γ_{20} under each HC increases slowly at first, then increases rapidly, and finally increases slowly again until it reaches its maximum γ_{max} .

The hot fog particles used to wet pollution layers are only 20-50 μm . At the beginning of wetting process, there are just separated small water droplets on the insulator surface. Only a small number of soluble salts of the pollution layer are dissolved into a small amount of conductive medium. Therefore, the increase rate of γ_{20} is small. With the deepening of wetness, the accumulated water on the insulator surface gradually increases, and a large amount of water infiltrates into the pollution interior. Salt components in the pollution interior are dissolved into conductive media in large quantities, and γ_{20} becomes to increase rapidly. The ability of contamination

to absorb water gradually reaches its maximum, and the dissolution rate of the conductive medium from the salt in the pollution decreases gradually, while the increase rate of γ_{20} decreases until it remains unchanged.

(4) Under every level of HC, the wetting velocity of the lower surface is lower than that of the upper surface.

The insulator shed has a downward inclination angle to make its upper surface more fully contact with moisture in the air. And the upper surface is affected by the gravity settlement of water droplets, which will also accelerate the wetting velocity of the pollution layer on the upper insulator surface.

Considering that the wetting velocity of the upper and lower surfaces with the same hydrophobicity is different, an improved driving force model for wetting process of the insulator pollution layer is proposed.

$$F = \gamma_g(1 + \cos \theta) + km_u g/d \tag{6}$$

where m_u is the water accumulation per unit area, kg; g is the acceleration of gravity, 9.78N/kg; d is the thickness of the pollution layer, m; k is the position coefficient, k of the upper surface is positive, and that of the lower surface is negative. Consequently, the driving force F of the lower surface is obviously smaller than that of the upper surface.

(5) When HC is 3-7, the local surface conductivity γ_{20} reaches its maximum value γ_{max} , and then begins to decrease after hovering around γ_{max} for some time. While, with the continuous development of wetting, γ_{20} of the HC1 and HC2 pollution layers does not decrease significantly.

The wetting appearance of HC7, HC4, HC3, HC2 and HC1 pollution layers is shown in Figure 4. The surface of HC7 HC4 and HC3 pollution layer has been covered by continuous water film when the pollution layers get wet for 15 min, 30 min and 40 min, respectively. With the continuous development of wetting, the water on the insulator surface is easy to flow and drops from the pollution layer. The lost water will take away a certain amount of soluble salt, resulting in the decrease of local surface conductivity after reaching the maximum value γ_{max} for a period of time. There is no water film formed on the HC2 and HC1 pollution layer when they get wet for 45 min, and 6 h, respectively. And the surface of HC1 pollution layer is obviously covered with separated water droplets. At this time, the water loss and pollution loss on the insulator surface can be ignored. It also means that the local surface conductivity value will not decrease.

The duration of local surface conductivity close to zero (DLSCCZ) and the saturated wetting time (SWT) are the time points of significant changes in the wetting degree of the pollution layer, and also the key time points of significant changes in insulation performance of the composite insulator. The maximum value of local surface conductivity (MVLSC) indicates the extremely terrible wetting degree of the pollution layer, and also reflects the insulation performance in case of severe damp. These three characteristic quantities are the key indexes to research the wetting characteristics of different hydrophobic pollution layers. On the basis of local

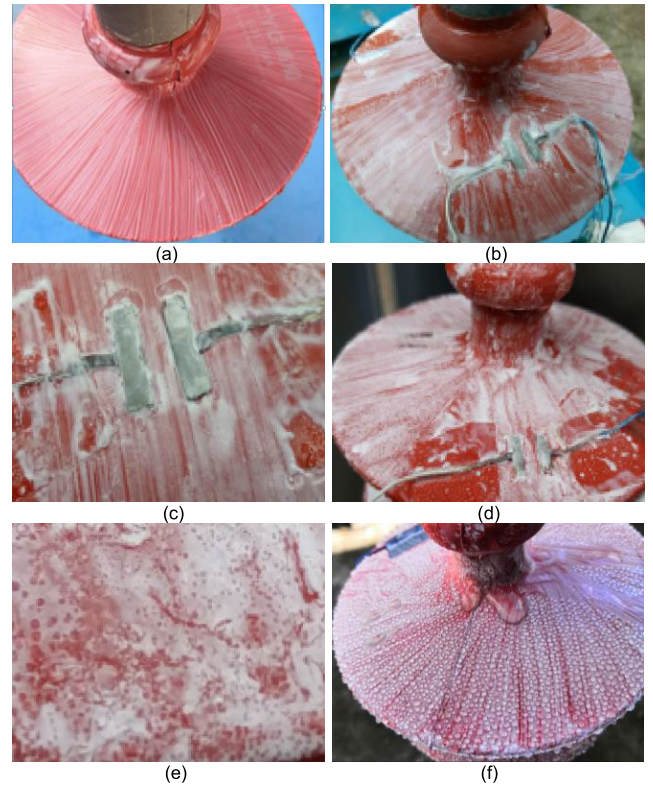


FIGURE 4. The wetting appearance of the pollution layer of composite insulators. (a) HC7: wetting for 15 min. (b) HC4: wetting for 30 min. (c) HC3: wetting for 40 min. (d) HC2: wetting for 45 min. (e) HC2: local enlarged drawing. (f) HC1: wetting for 6 h.

surface conductivity γ_{20} variation curves, this article extracts DLSCCZ, SWT and MVLSC, which are recorded as t_γ , t_b and γ_{max} . It should be noted that SWT refers to the time when the γ_{20} reaches the maximum value. The relationship between HC and t_γ , t_b and γ_{max} is shown in Figure 5 -Figure 7, respectively.

C. IMPACT OF HYDROPHOBICITY ON DLSCCZ

The impact of hydrophobicity on t_γ , the duration of local surface conductivity close to zero (DLSCCZ), is shown in Figure 5. With the enhancement of hydrophobicity, the value of t_γ will become larger. The t_γ of the HC7-HC1 upper surface are about 0.33, 0.83, 1.83, 2.83, 5.5, 7.17 and 7.67 minutes, respectively; and the t_γ of the HC7-HC1 lower surface are about 2, 4, 5.5, 7, 12, 15 and 18.5 minutes, respectively.

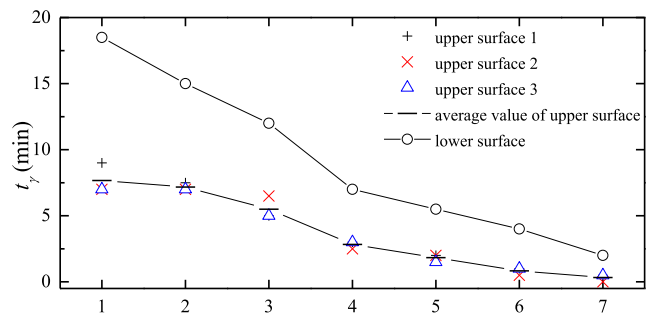


FIGURE 5. The relationship between HCs and t_γ .

The pollution layer has hydrophobicity due to the hydrophobicity migration of silicone rubber material. When the hydrophobicity becomes stronger, the repulsion of surface contamination to water will strengthen, the driving force F will decrease. It will be more difficult for water to penetrate into the pollution layer. The dissolved electrolyte will reduce. Therefore, when the hydrophobicity is enhanced, it will take more time to dissolve a certain amount of conductive medium to make γ_{20} increase.

D. IMPACT OF HYDROPHOBICITY ON SWT

The impact of hydrophobicity on t_b , saturated wetting time (SWT), is shown in Figure 6. The value of t_b increases with the improvement of hydrophobicity. The t_b of the HC7-HC1 upper surface are about 16.17, 20.83, 23.5, 29.67, 35.83, 41.83 and 44 minutes, respectively; and the t_b of the HC7-HC1 lower surface are about 24.5, 31, 36, 43, 52, 61 and 63 minutes, respectively.

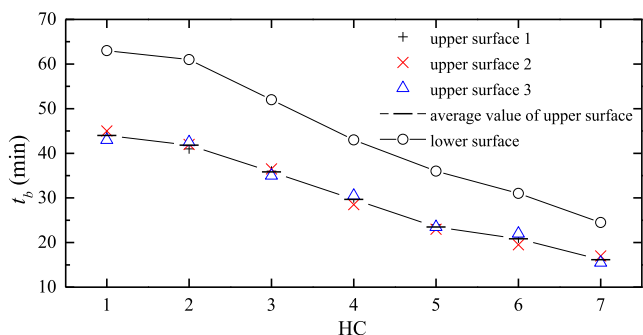


FIGURE 6. The relationship between HCs and t_b .

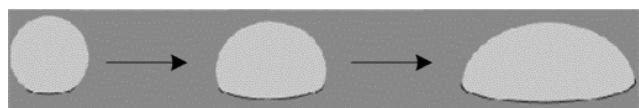


FIGURE 7. The change process of water droplets.

The hydrophobicity makes the surface pollution layer have the characteristic of keeping the water in the state of droplets rather than spreading out into water film. The shape of water droplets on the surface of the pollution layer is close to spherical when it is initially wetted. As the wetting progressed, the water droplets appear stretching phenomenon, and gradually transform from spherical to ellipsoid, as is shown in Figure 7. The stronger hydrophobicity makes water droplets closer to the sphere under the same wetting time. At this time, the direct contact area between the water droplets of the same mass and the surface pollution layer is reduced, and the dissolved electrolyte decreases accordingly. As is shown in Figure 4, continuous water film is formed on the surface of HC7-HC3 pollution layers when they are saturated wetted. But for the stronger hydrophobic pollution layer, the formation time of water film is later. Obviously, when the water film appears, the contact surface between the pollution

layer and the water is larger, and the wetting speed will also be accelerated. For the HC2 and HC1 pollution layers as is shown in Figure 4, only water droplets are formed when they are saturated wetted. The contact area between the pollution layer and the water is significantly less than that of HC7-HC3 pollution layers. Moreover, with the increase of hydrophobicity, driving force F will decrease, and it will take longer time for water to penetrate into the pollution layer and dissolve out the same amount of conductive medium. When the HC level decreases from 1 to 7, the dissolving speed of the salt inside the pollution layer increases gradually, and the time for the contamination to reach the maximum solubility is shorter.

E. IMPACT OF HYDROPHOBICITY ON MVLSC

The impact of hydrophobicity on γ_{max} , the maximum value of local surface conductivity (MVLSC), is shown in Figure 8. The value of γ_{max} augments with the decrease of surface hydrophobicity. The γ_{max} of the HC7-HC1 upper surface are about 133.03, 130.9, 130.2, 127.47, 119.8, 104.27 and 95.87 μS , respectively; and the γ_{max} of the HC7-HC1 lower surface are about 130.2, 128.1, 122.2, 118.6, 104.3, 74.78 and 71.5 μS , respectively.

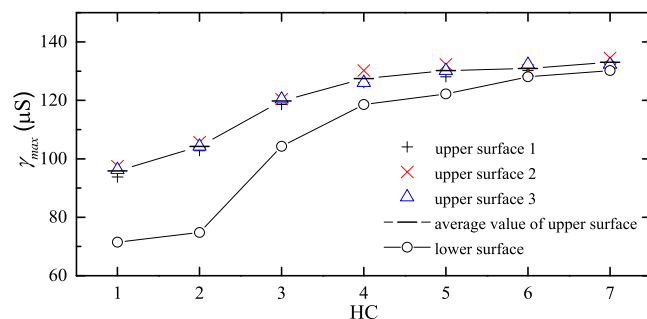


FIGURE 8. The relationship between HCs and γ_{max} .

The proportion of colorless and transparent pollution dissolved by water is higher. By contrast, the proportion of the white pollution dissolved by water is lower. As is shown in Figure 4, with the enhancement of hydrophobicity, the surface pollution gradually changes from colorless and transparent to white. This indicates that the effective solubility of the pollution decreases gradually. Hence, the maximum value of local surface conductivity γ_{max} decrease when HC level changes from 7 to 1. And the γ_{max} of HC1 pollution layer is only about 72% of that of HC7 pollution layer.

The driving force F is related to the hydrophobicity. The test results also show that the driving force F can explain the effective solubility of pollution to some extent. With the decrease of driving force F , the effective solubility of soluble salt will reduce.

IV. CONCLUSION

In this article, the wetting test of hydrophobic composite insulator was carried out in a wetting degree detection system by using the self-made phase angle difference device. The following conclusions are obtained:

1) Hydrophobicity has a significant impact on the wetting of the pollution layer on the composite insulator surface. The local surface conductivity of the strongly hydrophobic pollution layer will not rise immediately at the initial stage of wetting. Excellent hydrophobicity will make the duration of local surface conductivity close to zero (DLSCCZ) increase.

2) With the enhancement of the hydrophobicity of pollution layer, the repulsion of the pollution to water will be strengthened, the wetting speed slows down, and the saturated wetting time (SWT) increases.

3) Strong hydrophobicity reduces the effective solubility of soluble salt. With the enhancement of the hydrophobicity, the maximum value of local surface conductivity (MVLSC) decreases. MVLSC of HC1 pollution layer is only 72% of that of HC7 pollution layer.

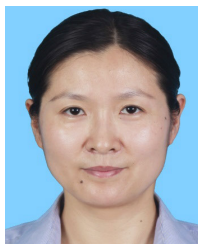
It should be noted that the voltage applied on the composite insulator is only a few volts in the wetting test. Hence, the drying effect of local arc on the pollution layer of insulators was not considered, and it is difficult to establish a direct relationship between the local surface conductivity and the polluted flashover at present.

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