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Hydrophobicity Transfer Property of Silicone Rubber Material

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Abstract: The unique hydrophobicity transfer property of silicone rubber material ensures its good hydrophobicity when being polluted with pollutants. Earlier studies have shown that the migration of low molecular weight (LMW) components of polysiloxane from the bulk to the surface of silicone rubber is the root cause of the hydrophobicity transfer property. This migration process is influenced by the ambient conditions. In this paper the influence of temperature on the transfer property is investigated, and transfer characteristics on HTV-SR have been found which exhibit a saltus between 50℃ and 55℃. The influence of humidity on the transfer property with different kinds of pollutants is investigated using the saturated salt solution method to control the relative air humidity. The results show that the influence of relative humidity is related with the hygroscopicity of soluble and non-soluble substances in pollutants on the surface. The hydrophobicity transfer property of HTV-SR polluted with 10 different kinds of inert materials is investigated, and the results show that different kinds of pollutants have a great influence on the hydrophobicity transfer property of HTV-SR. DC artificial pollution tests were conducted in Yunnan, China. The results show that the pollution flashover performance of composite insulators is closely related to the hydrophobicity state of the surface. The flashover voltage of composite suspension insulators rises with the increase of the transfer time and the mass fraction of kieselguhr in pollutants.

Keywords: Hydrophobicity transfer; ambient temperatur and humidity; pollutants;flashover performance;static contact angle

1. Introduction

IN recent years, silicone rubber products have been widely used in power systems to combat pollution flashover problems. In China, composite insulators with a housing consisting of high temperature vulcanizing silicone rubber (HTV-SR) have been widely applied since the 1980s, and have shown excellent pollution flashover performance ever since. Only in China, there are nowadays more than 5,000,000 composite insulators in service on transmission lines [1-3]. Another application of silicone rubber products is the usage of room temperature vulcanizing silicone rubber (RTV-SR) as coating for insulators. It has been widely used to coat porcelain and glass insulators in the power system of China since the 1980s, especially in wet and heavily polluted conditions, showing excellent performance since then. RTV coating has now been accepted as one of the most important measures to resist pollution flashover on porcelain and glass insulators in China [4-6].

Good hydrophobicity and the unique hydrophobicity transfer property of silicone rubber materials is the basic reason for the excellent pollution flashover performance of silicone rubber products. Earlier studies have shown that the hydrophobicity transfer of silicone rubber materials is mainly due to a diffusion process, whereby low molecular weight (LMW) polymer chains from the bulk migrate to the surface to recreate a low energy surface [6-10]. Even when the surface loses hydrophobicity due to severe weather conditions like corona or long-time wetting conditions, the hydrophobicity recovers with time due to further LMW transfer from

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the bulk [11]. When their surface is polluted, silicone rubber materials also tend to coat pollutants deposited on the surface of the insulator sheds thus mitigating the degradation of the hydrophobicity by pollution.

As mentioned above, the hydrophobicity transfer property is the key point why silicone rubber products can combat pollution flashover problems. However, in actual service, the hydrophobicity transfer property of silicone rubber materials is affected by external factors, such as the ambient environment and pollutants [12-14]. A lot of investigations have been carried out on the factors influencing the hydrophobicity transfer property of silicone rubber materials. Results show that the ambient environment and pollutants greatly influence the speed and degree of the hydrophobicity transfer. However, most of these investigations have not been carried out systematically and the influence of ambient temperature, ambient humidity and pollutants on hydrophobicity transfer property has not been thoroughly reported. In-depth research should thus be carried out on these problems.

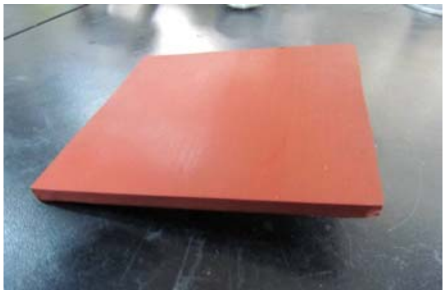
In this paper the hydrophobicity transfer characteristics of silicone rubber material are investigated under different ambient temperature and humidity to get thorough results. The hydrophobicity transfer characteristics in the presence of kieselguhr and kaolin pollutants as well as a number of natural pollutants are investigated and compared in order to determine how best to simulate the behavior of natural pollution using artificial pollutants and their mixtures. In addition, the pollution flashover performance of composite suspension insulators is investigated after different transfer time and with different compositions of pollutants.

2. Sample and Test Method

A. The test sample

A typical HTV-SR and RTV-SR sample is shown in Figure 1. The size of the sample is 100 mm*100 mm*5 mm. The pollutants were applied to the surface by the solid layer method [15], in which a contaminant solution consisting of pollutants and distilled water was used to coat the sample surfaces. The non-soluble deposit density (NSDD) in each case was 1.0mg/cm^2, the equivalent salt deposit density (ESDD) was 0.1 mg/cm^2.

The test method



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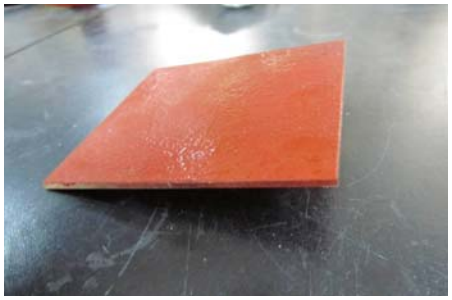

(b)

Figure 1. Test samples made of (a) HTV and (b) RTV

B. *The test method*

At present there are two practical methods available for determining the hydrophobicity of silicone rubber material [16-17]. The first is the determination of the Wettability Class (HC) by the spray method, and the second is the contact angle (CA) method. The spray method is generally used to assess the hydrophobicity level of insulators on site, but does not allow for quantitative and comparative analysis. Another disadvantage of the HC method is that it is easily affected by subjective factors of different researchers, so in this paper the CA method was used to determine the hydrophobicity of silicone rubber.

The OCA20 optical contact-measuring device was used to measure the contact angle of the samples. It was found that using 4 droplets on one part of a sample, the measurement error can be acceptable, within ±1°. So, 4 droplets of distilled water, each with a volume of 2 μl were allowed to fall randomly onto the surface. The static contact angle was obtained by using the special software of OCA20. As is already known, after the droplet falls onto the surface, the static contact angle of the droplet decreases gradually with the increase of time. Gravity, absorption of pollutants and evaporation should be responsible for this phenomenon. It was found that the static contact angle decreases greatly and is gradually getting steady during the first 20 seconds after positioning of the droplet. Therefore, the measurements in this paper were performed 20 seconds after the droplets fell onto the surface when there was no more obvious decrease of the static contact angle. Pictures of typical droplet shapes are shown in Figure 2.

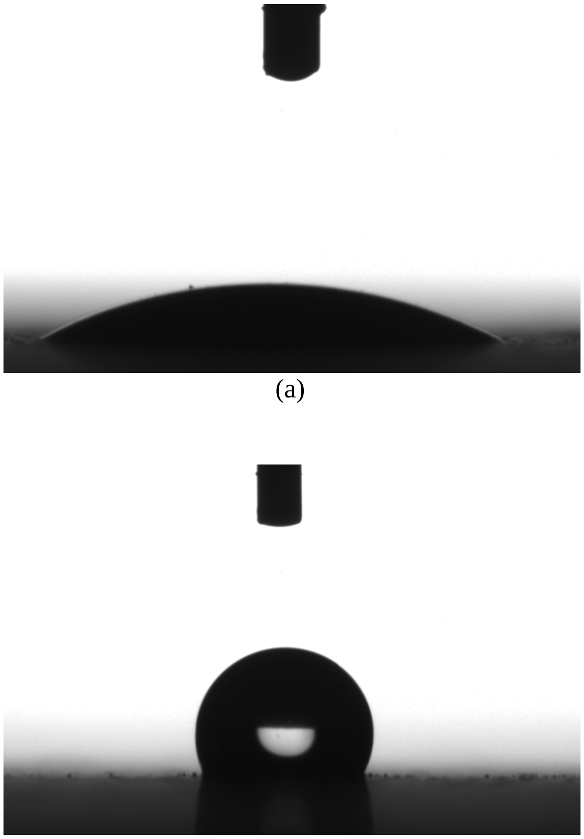
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Figure 2. Water droplets on (a) hydrophilic and
(b) hydrophobic silicone rubber surfaces with pollutants

3. Results and Discussion

A. Influence of ambient temperature

High temperature condition

The process of hydrophobicity transfer was measured on HTV-SR and RTV-SR samples at different ambient temperature. The ambient temperature was controlled by an incubator whose accuracy was ±1℃. The pollutants were kaolin and NaCl and the following pollution severity was adjusted, NSDD = 1.0mg/cm^2 and ESDD = 0.1mg/cm^2.

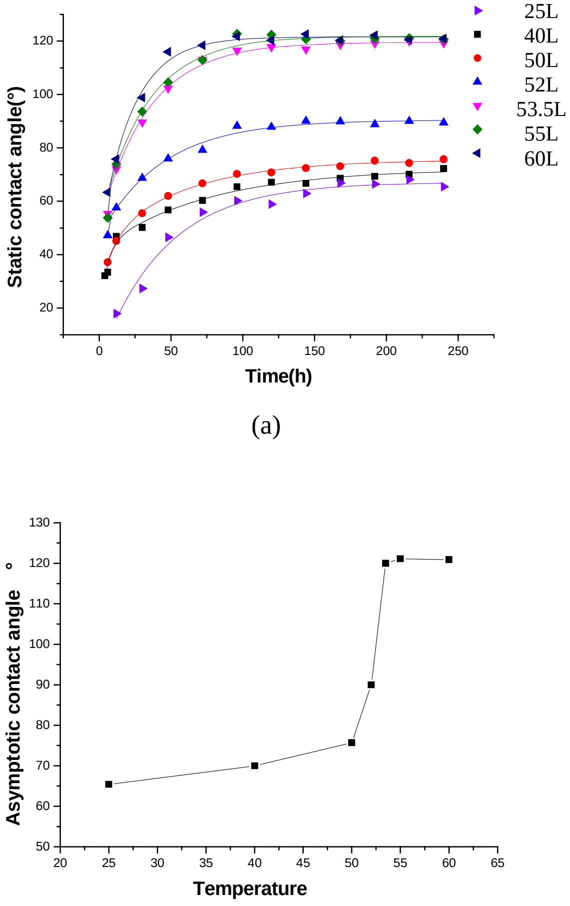

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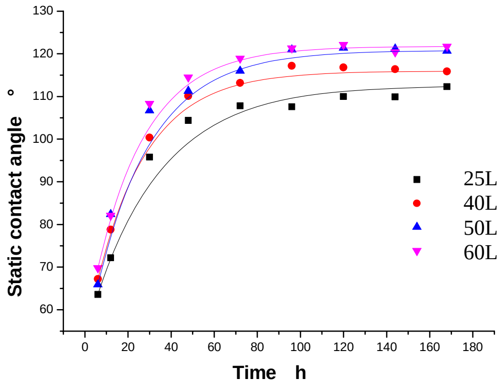
Figure 3. Hydrophobicity transfer characteristics of HTV-SR under different ambient temperature, (a) hydrophobicity transfer speed, (b) final asymptotic value of the contact angle

As we can see in Figure 3, after polluting the surface of HTV-SR samples, the static contact angle increases with the increase of transfer time, and gradually gets to a stable value. The hydrophobicity transfer speed and the asymptotic value of the contact angle both increase with the ambient temperature. It can also be seen that there is a saltus of the asymptotic contact angle between 50℃ and 55℃, where the asymptotic contact angle leaps from below 90° to above 90°. It can be assumed that diffusion of LMW from bulk to pollutants greatly increases when the temperature arises from 50℃ to 55℃.

The hydrophobicity transfer characteristics of RTV-SR sample are shown in Figure4.



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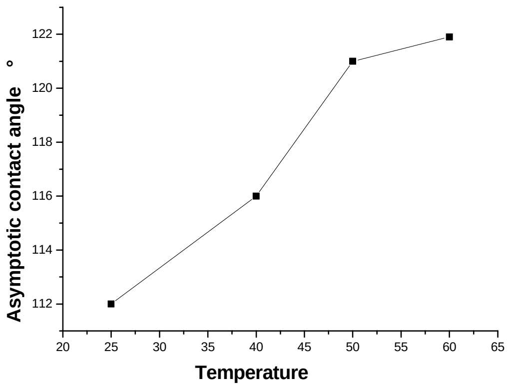


(b)

Figure 4. Hydrophobicity transfer characteristics of RTV-SR under different ambient temperature, (a) hydrophobicity transfer speed, (b) final asymptotic value of the contact angle

It can be seen that the hydrophobicity transfer speed and the asymptotic value of the contact angle also increase with the ambient temperature, albeit in a way different from HTV-SR. No saltus of the asymptotic contact angle was observed but a roughly linear increase with the ambient temperature appeared between 25℃ and 60℃.

It is also necessary to investigate the hydrophobicity transfer property of silicone rubber at lower temperatures as well, because composite insulators have shown bad pollution flashover performance in recent years. A special semiconductor temperature control platform (Figure 5) was used, with which a stable temperature could be maintained during the measurement of the hydrophobicity transfer. That way, condensation on the pollution surface during the measurement procedure could be avoided as well.

Low temperature condition

The process of hydrophobicity transfer was measured on HTV-SR at ambient temperatures of 5℃, 10℃ and 25℃, respectively. The pollutants were kaolin and kieselguhr with NSDD=1.0 mg/cm^2, and ESDD=0.1 mg/cm^2.

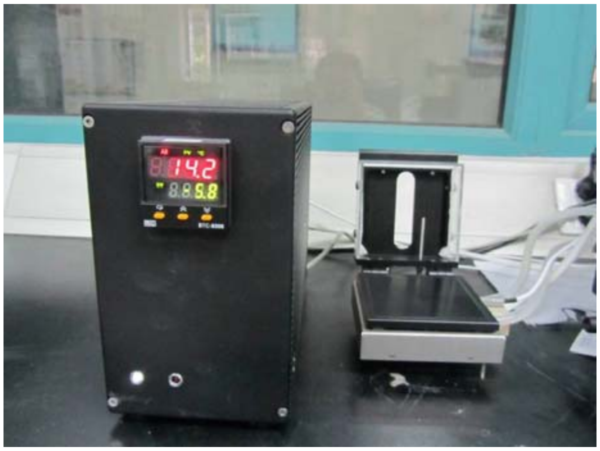
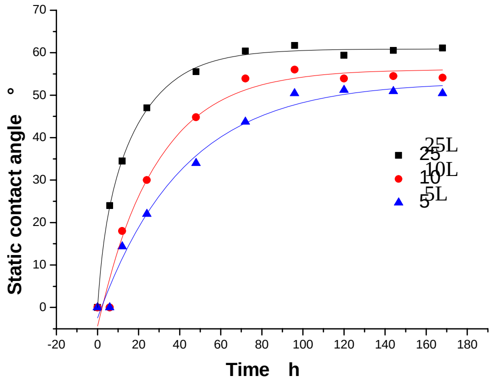


Figure 5. Semiconductor temperature control platform



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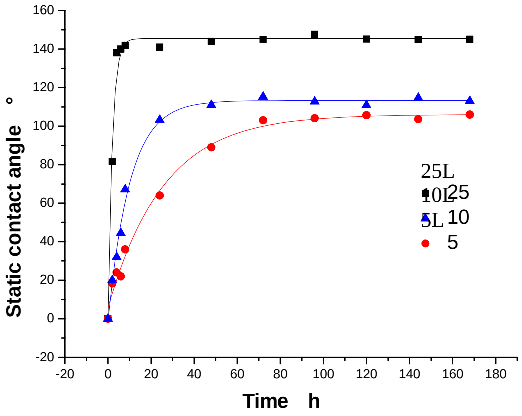


(b)

Figure 6. Hydrophobicity transfer characteristics of HTV-SR under different low temperature conditions, (a)polluted with kaolin, (b) polluted with kreselguhr

It can be seen in Figure 6 that the hydrophobicity transfer speed and the asymptotic value of the contact angle decrease significantly as the temperature drops from both 25℃ to 10℃ and 10℃ to 5℃. Therefore, it can be concluded that when silicone rubber products are exposed to low temperature conditions for a long period, pollutants build up gradually on the surface while hydrophobicity cannot transfer from bulk onto the pollution surface as quickly as under high temperature conditions. Pollution flashover will thus be more likely to happen at low temperature conditions which have to be considered as a kind of harsh conditions for the service of silicone rubber material.

B. *Influence of ambient humidity*

In this paper, the ambient humidity was controlled by using the saturated salt solution method according to EN ISO 483 [18]. The polluted samples were put into a closed container with different kinds of saturated salt solutions. The relative humidity in the container stayed constant. The used solutions and the corresponding constant relative humidity in the closed container are shown in Table 1.

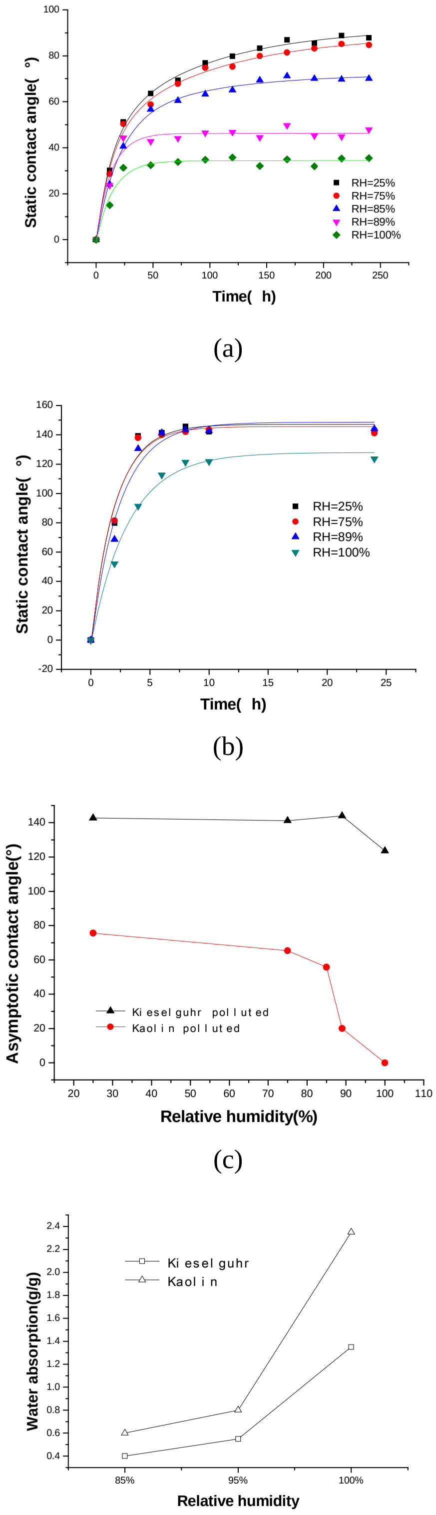
Table 1. Saturated salt solutions and their corresponding constant relative humidity

Saturated solutions	Theory humidity	Actual humidity
desiccant	-	25%
NaCl	75%	75%
KCl	84%	85%
KNO_3	92%	89%
K_2SO_4	97%	95%
distilled water	100%	100%

Pollutants with no soluble substances

Hydrophobicity transfer characteristics of HTV-SR when polluted with only kaolin or kieselguhr is shown in Figure 7. It can be seen that when polluted with kaolin, the hydrophobicity transfer speed and the asymptotic value of the contact angle are both greatly influenced by the relative humidity. Especially when the relative humidity is high, the transfer speed and the asymptotic value of the contact angle decrease significantly. The situation is different in case of HTV-SR samples polluted with kieselguhr. When the relative humidity reaches 100%, the transfer speed decreases and the asymptotic value of the contact angle drops from 140° to about 120° while there is almost no influence on the hydrophobicity transfer characteristics at relative humidity below 100%.

The difference between kaolin and kieselguhr in different humidity can be explained by the theory of hygroscopicity, i.e. the water absorption per unit mass of kaolin and kieselguhr (Figure 8). It can be seen that the hygroscopicity of kaolin is much higher than that of kieselguhr. At relative humidity of 85%, kaolin exhibits a 50% greater hygroscopicity than kieselguhr. When the relative humidity reaches 100%, the difference is more obvious so that kaolin has 68% greater hygroscopicity than kieselguhr. Due to the higher hygroscopicity of kaolin, the amount of moisture stored in the Kaolin pollutant is bigger than in the kieselguhr pollutant, what blocks the transfer of LMW from bulk to the surface pollutant to some extent. Therefore, the influence of the relative humidity on kaolin-polluted HTV-SR samples is greaterthan on the kieselguhr-polluted samples, especially in high humidity conditions.



(a)

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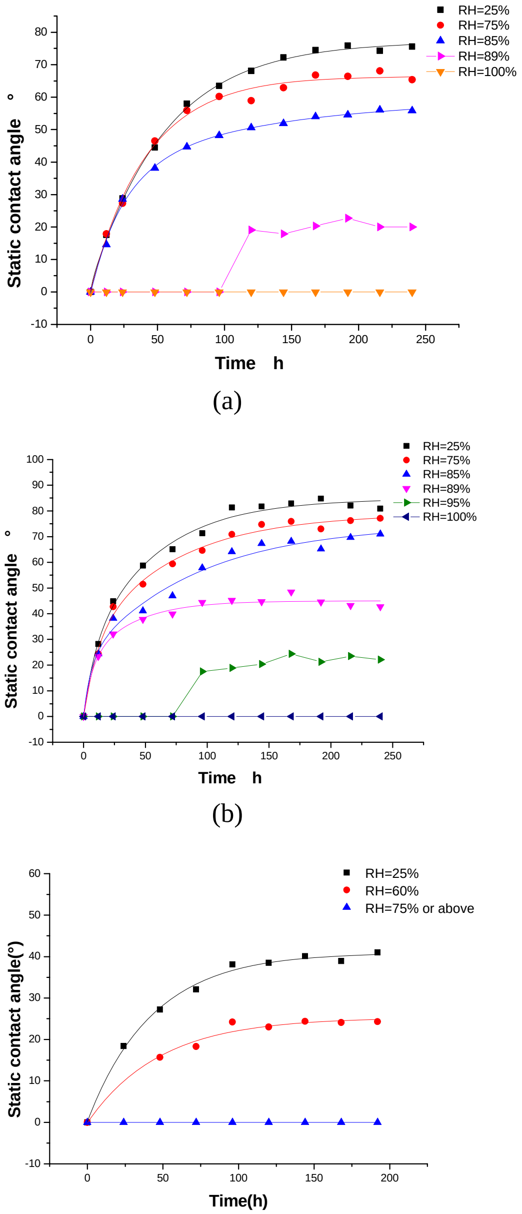
Figure 8. Hygroscopicity of kieselguhr and kaolin at different relative air humidity

Pollutants with different kinds of soluble substances

In practical service, pollutants on insulators consist of various kinds of soluble substances. Different soluble substances show different transfer characteristics in certain humidity conditions. In this paper, 3 kinds of soluble substances were chosen to pollute the HTV-SR samples: 1) NaCl is the most commonly used soluble salt for artificial pollution tests on insulators; 2) $CaSO_4$ is known as the most common salt on naturally polluted insulators in China; 3) Sugar is a special kind of soluble substance on insulators in some area. The hydrophobicity transfer characteristics of HTV-SR polluted with different kinds of soluble substances are shown in Figure 9. The non-soluble pollutant is kaolin.



(a)

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Figure 9. Hydrophobicity transfer characteristics of HTV-SR polluted with different kinds of soluble substances, (a) kaolin and NaCl, (b) kaolin and $CaSO_4$, (c) kaolin and sugar

The results in Figure 9 show that when being polluted with kaolin and different kinds of soluble substances, the hydrophobicity transfer speed and the asymptotic value of the contact angle decrease when the relative humidity increases. That is no matter whether the soluble substances are NaCl (Figure 9a), $CaSO_4$ (Figure 9b), or sugar (Figure 9c). However, the characteristics of the hydrophobicity transfer with different kinds of soluble substances differ from each other when the relative humidity is the same. In Figure 9 (a), the hydrophobicity transfer speed and the asymptotic value of the contact angle decrease greatly when the relative humidity reaches values higher than 89%, thus 89% can be considered as the critical relative humidity for pollutants with NaCl. Similarly, it can be seen in Figure 9 (b) that the critical relative humidity for pollutants with $CaSO_4$ is 95%. Likewise, the critical relative humidity for pollutants with sugar is 60%. When the relative air humidity rises above the critical value, an obvious damping phenomenon can be seen on the surface of pollutants, and the hydrophobicity transfer speed and the asymptotic value of the contact angle decrease greatly.

The difference of the critical relative humidity of NaCl, $CaSO_4$ and sugar can also be explained by the theory of hygroscopicity. The water absorption per unit mass of different pollutants is shown in Figure 10. It can be seen that pollutants containing NaCl and sugar have the highest hygroscopicity being able to absorb much more water than pollutants containing $CaSO_4$ and no soluble substances, even at low relative humidity like 75%. It can be concluded that the hygroscopicity of pollutants and the hydrophobicity transfer characteristics are closely correlated. The higher the hygroscopicity of pollutants, the lower the hydrophobicity transfer speed and the smaller is the asymptotic value of the contact angle. Meanwhile, the critical relative humidity decreases as well the higher the hygroscopicity of pollutants is.

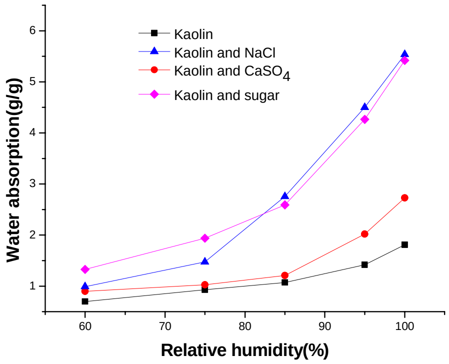


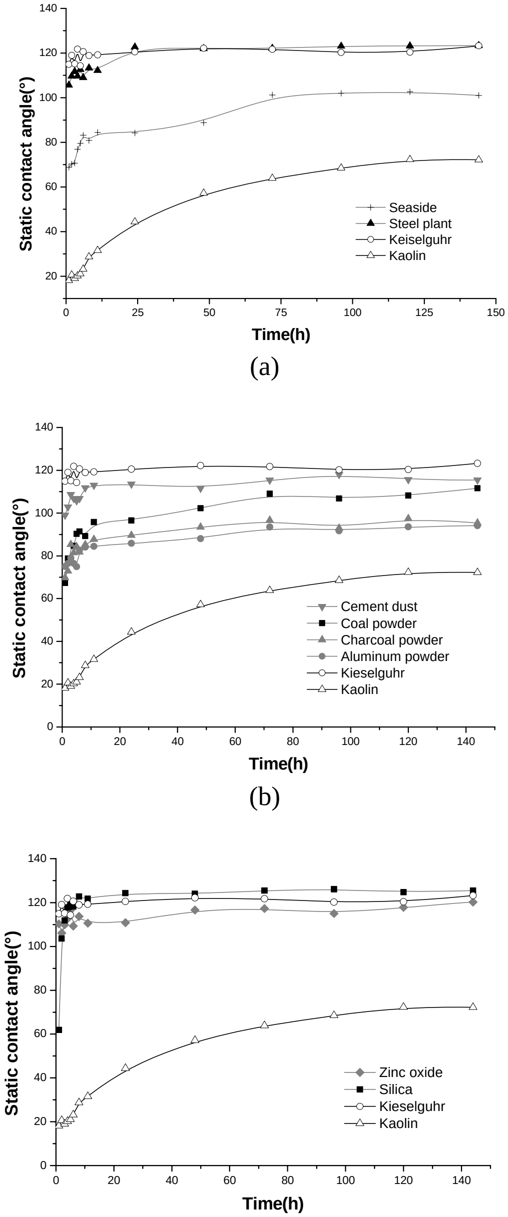
Figure 10. Hygroscopicity of pollutants containing different kinds of soluble substances with relative humidity

C. *Influence of pollutants*

Under natural pollution conditions, the components of pollutants in different areas differ significantly from each other. When being polluted with different kinds of non-soluble pollutants, the hydrophobicity transfer characteristics of HTV-SR may be quite a bit different. The process of hydrophobicity transfer was measured on the surface of HTV-SR samples which were polluted with 10 different kinds of pollutants. Some pollutants were natural pollution accumulated on insulators near the sea side and near a steel plant; powdered coal, charcoal, zinc oxide, aluminum, cement, and silica were used to represent possible natural pollutants as well as kaolin and kieselguhr. The coal and charcoal dust could represent pollutants originating from nearby coal burning factories or forest fires. Metal oxides, cement and silica represent pollutants originating from various industrial processes, from a cement factory and from dust storms, respectively.

The results are shown in Figure 11. In each graph the curves for kieselguhr and kaolin are shown for comparison. In Figure 3(a), the hydrophobicity transfer characteristics are shown for HTV-SR samples coated with pollutants gained by scraping from insulators located near a steel plant, near the sea side or near a cement factory. Figure 11(b) shows the hydrophobicity transfer characteristics when coal, charcoal and aluminum powder were used as the pollutants. In Figure 11(c), the hydrophobicity transfer onto two other inert materials, i.e. zinc oxide and silica, is shown.

It is clear from Figure 11 that several of the inert pollution materials behaved in a manner very similar to that of kieselguhr. All pollutants became more hydrophobic than kaolin in a significantly shorter time. Indeed, the curves of most of the materials reached their asymptote within 25 hours while the hydrophobicity transfer onto kaolin was completed not before 144 hours.



(a)

(b)

(c)

Figure 11. The transfer of hydrophobicity for 10 types of naturalinert pollutants: (a) from insulators located within 1000m from the sea side, a steel plant, and a cement factory, (b) coal, charcoal and aluminum powder, (c) zinc oxide and silica

D. *Flashover performance of composite insulators*

The pollution flashover performance of composite insulators is considered to be closely related to the hydrophobicity state of the surface. In this paper, DC artificial pollution tests were conducted in Yunnan, China, to obtain the flashover performance of composite insulators in different conditions.

Influence of transfer time on flashover voltage

It can be concluded from the former sections that the polluted surface of insulators shows different contact angles after different transfer times. This influences the shapes of droplets in the wetting process, what again influences the flashover performance of insulators. In this paper, the influence of the transfer time on the DC pollution flashover performance of composite suspension insulators was investigated at ambient temperatures of 25±2℃ and 15±℃, respectively. Kaolin was used as pollutant. The results are shown in Figure 12.

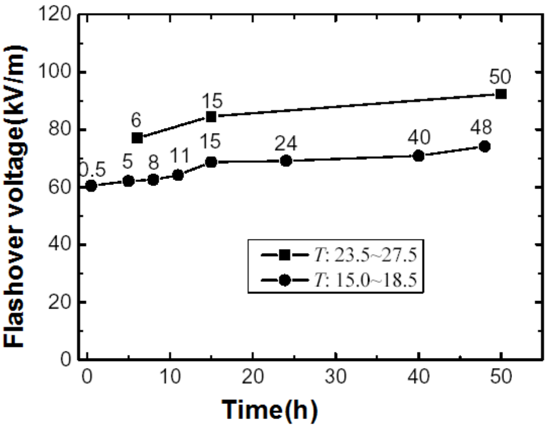


Figure 12. Influence of the transfer time on the flashover voltage per insulation distance of composite suspension insulatorsat different ambient temperatures

It can be seen in Figure 12 that the flashover voltage per insulation distance rises with the transfer time. That is mainly because of the hydrophobicity transfer making the pollution surface more hydrophobic as time goes by.

Influence of pollutants on flashover voltage

It has been mentioned in section C that different kinds of pollutants on the surface influence the hydrophobicity transfer characteristics of silicone rubber material significantly. The pollution flashover performance of composite suspension insulators polluted with different adhering pollutants versus the transfer time is shown in Figure 13. The mixed pollutants consisted of kaolin and kieselguhr, where P_k indicates the mass fraction of kieselguhr in the mixed pollutants.

It can been seen in Figure 13 that the flashover voltage rises with the transfer time no matter which P_k value is adjusted. However, when pollutants are composed of only kaolin (P_k =0%), the flashover voltage is relatively low and rises slowly with the increase of the transfer time. A higher mass fraction of kieselguhr in the pollutants leads to a higher flashover voltage which rises faster with the increase of the transfer time.

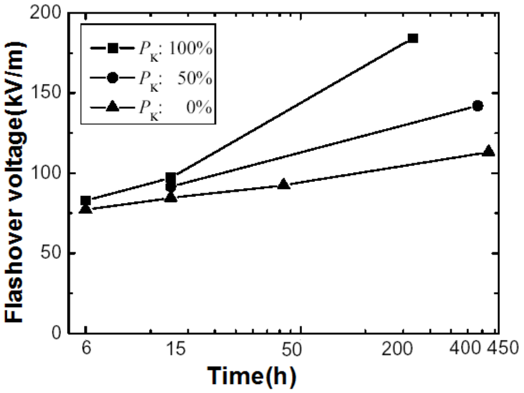


Figure 13. Influence of the mass fraction of kieselguhrP_k in mixed pollutants on the flashover voltage per insulation distance of composite suspension insulators

4. Conclusions

(1) The hydrophobicity transfer property of silicone rubber is influenced by the ambient temperature. In high temperature conditions, the transfer speed and the asymptotic value of the contact angle on HTV-SR have a saltus between 50℃ and 55℃. An extreme increase in the diffusion rate of decomposed LMW in HTV-SR is presumed to be responsible for this.

(2) The transfer speed and the asymptotic value of the contact angle decrease greatly in low temperature conditions, no matter whether the pollutants are kaolin or kieselguhr.

(3) The hydrophobicity transfer property of HTV-SR is influenced by the relative air humidity. With the increase of humidity, the asymptotic value of the contact angle decreases.

(4) The influence of the relative humidity is related with the hygroscopicity of soluble and non-soluble substances in pollutants. The higher the hygroscopicity, the slower the hydrophobicity transfer and the smaller is the asymptotic value of the contact angle. As to pollutants consisting of kaolin and different kinds of substances, there is a critical relative humidity, above which the wetting phenomenon becomes obvious and the transfer property is attenuated.

(5) The kind of pollutant has a great influence on the hydrophobicity transfer property of HTV-SR.

(6) The pollution flashover performance of composite insulators is closely related to the hydrophobicity state of the polluted surface. The flashover voltage of composite suspension insulators rises with the increase of both, the transfer time and the mass fraction of kieselguhr in pollutants.

Acknowledgment

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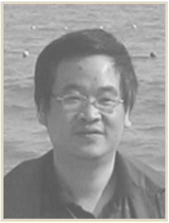

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