Electric Field Distribution of Soluble Salt Deposition on the Surface of Insulators in Railway Overhead Lines*

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Abstract: Different constituents of soluble salts have different effects on the insulation performance of insulators. To study the electric field distribution of soluble salt deposition on the surface of high-speed railway insulators, a two-dimensional model of the cantilever insulator electrostatic field and constant-current field with soluble salt deposition is constructed. The simulation results indicate that the relative dielectric constant of dry pollution is the main factor that affects the electric field distribution on the surface of the insulator. The electric field intensity is arranged in the following order: $CaSO_4$>KNO_3>$NaNO_3$>K_2SO_4>NaCl>$MgSO_4$, and the conductivity of each dirty liquid in the wet state becomes a key factor affecting the electric field distribution, which is specifically shown as sodium chloride>nitrate>sulfate. The simulation results are compared with existing test results to verify that they were correct. It is also found that the electric field intensity of the insulator with good hydrophobicity is slightly greater than that of the insulator without hydrophobicity. The results provide a theoretical basis for the classification of regional pollution levels and the testing of insulator contamination in the laboratory.

Keywords: Catenary insulator; soluble salt composition; electric field intensity; electrostatic field; constant-current field

1 Introduction

Insulators are the main pieces of equipment used to ensure electrical insulation of transmission lines and have been widely used in railway lines [1]. Currently, research on the insulation performance of insulators is based on the equivalent salt density method. Most scholars use NaCl for equivalent insulator surface contamination for testing in the laboratory; however, insulator surface contamination is composed of multiple components, which leads to a certain gap between the laboratory results and the those from the natural environment. A few scholars have begun to pay attention to the influence of other pollution components on the electrical performance of insulators. Various researchers [2-6] found that the soluble salt $CaSO_4$ on the surface of insulators accounts for 20%-60% of the total pollution, while NaCl only accounts for 10%-40%. Huang et al. [7] found that the content of $CaSO_4$ affects the peak value of the leakage current of the composite insulator; Zhang et al. [8] found that increasing the proportion of $CaSO_4$ will increase the flashover voltage of insulators and explained the reason for this phenomenon from the perspective of particle conductivity and the ionization process affecting surface arcing.

In addition to analysis of the flashover characteristics of insulators from the microscopic point of view of pollution components, the operating state of the insulators has also been analyzed through experiments and numerical simulations, and the flashover characteristics of the insulators under macroscopic conditions have been obtained [9-12]. However, testing results are highly dispersed and the test cycle is long, and the test results are often far from the actual situation. The numerical simulation method is simple and easy to implement. It can accurately

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reflect the operating status of the insulator under multiple factors, and the cost is low. Wang et al. [13] obtained the potential and electric field changes for insulator processed from corona discharge to flashover through simulation analysis of insulators in the operating state, which reflects the influence of various factors on the operating state of insulators. Lv et al. [14] found that water droplets have a greater impact on the distortion rate of the electric field through simulation studies on the position, spacing, and parameters of the water droplets attached to the surface of the insulator. However, there is no relevant literature in which simulation methods are used to analyze the surface electric field of insulators with different pollution components. Most of them entail modeling and simulation based on the equivalent salt density method, which limits the simulation results.

In this study, to explore the influence of various pollution components on the surface electric field distribution of composite insulators, the surface soluble salts of FQBJ-25/12 composite insulators on railway catenary cantilevers at Xining Station, Qinghai Province, were analyzed, and the composition and specific gravity of the pollution were obtained. A simplified two-dimensional model of the insulator was constructed, and the electric field distribution of each pollution component in dry and wet states was obtained through simulation. It was found that the influence of pollution on the electric field distribution mainly depends on the relative permittivity of dry pollution and the conductivity of wet pollution. According to the characteristics of the composite insulator, the influence of the soluble salt components of the insulator on its surface electric field in hydrophobic and hydrophilic states was then studied. The research results explain the reasons for the influence of different pollution components on the electrical performance of insulators, provide a theoretical basis for the evaluation of insulators' operating conditions in natural environments, and provide a new test method for the design of laboratory pollution tests and a precise division of regional pollution levels.

2 Analysis of surface contamination of the cantilever insulator

The composition of insulator surface pollution is different in the natural environment, exhibiting a large regional gap and surrounding environment differences. According to Song et al. [15], the surface contamination of insulators is mainly composed of inorganic soluble salts, inorganic insoluble substances, and organic compounds. The insoluble matter mainly plays a role in the water adsorbed on the surface of the insulator. The higher the insoluble matter content within a certain range, the greater the water content on the surface of the insulator and the more dissolved soluble salts. There is relatively little research on organic compounds at present, and the technology for determining organic components is not mature enough and has not attracted the attention of most scholars. The main influence on the electrical properties of insulators is the presence of inorganic soluble salts. In this study, the pollution components on the surface of insulators in four different regions (the Hebei saline-alkali area, Xining station of the Qinghai-Tibet line, Xianyang farmland, and Henan section of the Ha-Zheng line) were measured. Fig. 1 shows the composition of the pollution components in each region.

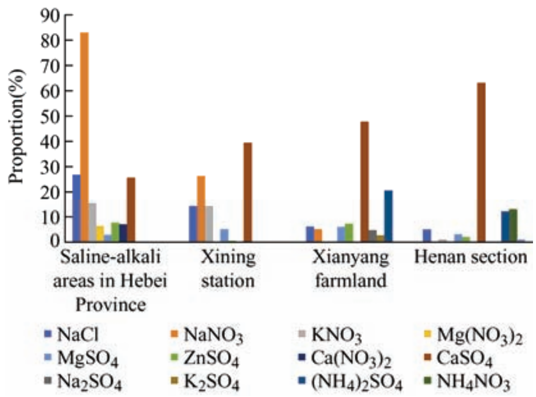

Fig. 1 Composition and proportion of insulator pollution in different areas

It can be seen from Fig. 1 that the content of $NaNO_3$ in the saline-alkali area of Hebei Province is significantly higher than that of the other three places, while the content of $CaSO_4$ in the other three places is the highest. The content of $CaSO_4$ on the surface of the insulators in the Henan section of the Ha-Zheng line is higher than other pollution contents, and there are many kinds of pollution in the area. The proportion of pollution on the surface of insulators in Xianyang farmland is relatively even, but there are many kinds of pollution, which is not conducive to research. In summary, it is reasonable to choose the Xining Station on the Qinghai-Tibet Line as the research subject.

Analysis of the pollution components on the surface of the insulators at Xining Station revealed that $CaSO_4$ accounted for the largest proportion, reaching 39.5%; the content of $NaNO_3$ ranked second, accounting for 26.2%; and the content of more common soluble salt NaCl was significantly less than that of $CaSO_4$ and $NaNO_3$ (only 14.2%). Moreover, the proportions of KNO_3, $MgSO_4$, K_2SO_4, and $ZnSO_4$ were all <10%, and their contents were relatively low, with $ZnSO_4$ salt accounting for only 0.6%. In the following modeling calculation process, the above-mentioned pollution components are used as the object to explore their influence on the surface electric field of insulators.

3 Simulation model

3.1 Electrostatic field model

Based on the basic operating conditions of OCS (Overhead Contact System) insulators, an AC power supply with a power frequency of 50 Hz was selected. Because the wavelength of the AC power is 6 000 km, which is much greater than the insulation height of the insulator, the electric field is stable at any moment. According to Zhang et al. [16], the finite element method can be used to study and analyze the electrostatic field problem, and a two-dimensional insulator model was established. The differential equation and boundary conditions satisfied by the electrostatic field are given by

$$\begin{cases} \nabla \cdot \boldsymbol{D} = 0 & D_{1n} = D_{2n} \\ \nabla \times \boldsymbol{E} = 0 & E_{1t} = E_{2t} \end{cases} \quad (1)$$

where $\boldsymbol{D}$ is the electric displacement vector, $\boldsymbol{E}$ is the electric field strength vector, n indicates the normal component, t indicates the tangential component, and 1 and 2 are the mediators.

3.2 Constant-current field model

In the process of calculating the surface electric field of the insulator, the conductivity of the surface pollution solution should be considered to establish a constant-current field model. Both the electric current field and the electrostatic field follow similar physical laws in mathematical form.

The boundary conditions for the constant-current field are

$$\begin{cases} \nabla \cdot \boldsymbol{J} = 0 & J_{1n} = J_{2n} \\ \nabla \times \boldsymbol{E} = 0 & E_{1t} = E_{2t} \end{cases} \quad (2)$$

where $\boldsymbol{J}$ is the current density vector.

3.3 Cantilever insulator model and relevant parameter settings

As a composite catenary cantilever insulator currently used on a large scale, compared to porcelain insulators, composite insulators are lighter in weight, sustainable insulation works longer, smaller in size, higher in mechanical strength, and better in resistance to pollution. Therefore, the composite insulator FQBJ-25/12 was selected for modeling. The insulator is large and has one small shed. The parameters of the insulator are listed in Tab. 1.

Tab. 1 Structural parameters of insulator

Parameter	Value
Model	FQBJ-25/12
Structural height H/mm	760±20
Arcing distance h/mm	488
Diameter of insulator shed D/mm	192/140
Diameter of insulator rod d/mm	80
Creepage distance L/mm	≥1 400

COMSOL Multiphysics software was used to study the distribution of the electric field in the space of the simplified insulator model, and a two-dimensional insulator model was established. A finite field was set up to solve for the electric field intensity of an insulator instead of an infinite field, with an area of a factor of ~15 greater than that of the insulator. A two-dimensional simplified insulator model is illustrated in Fig. 2.

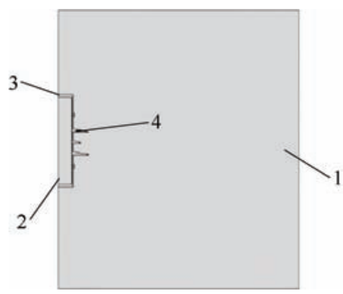

Fig. 2 Insulator finite field model

1. Air 2. Insulator mandrel
3. Metal fittings 4. Insulation sheath

The composite insulator in the finite domain is composed of four parts: air, insulator mandrel, metal fittings, and insulation sheath. The materials and related parameters of each part are given in Tab. 2 [17].

Tab. 2 Simulation parameter setting table

Parts	Material	Relative dielectric constant	Electrical conductivity
Air	Air	1	0
Mandrel	The glass fiber	6	0
Insulating sheath	Silicone rubber	4.3	10^{-12}
Hardware	CZ42 (alloy)	9.34	3.5×10^{7}

The operating voltage of the railway catenary is the single-phase alternating current supplied by the traction substation as the power source. According to the Ref. [18], compared with the AT (Auto transformer) power supply, the use of a direct power supply with a return line (TRNF) is beneficial for reducing the voltage loss of the traction power supply system and the impact of negative sequences on the power system. At the same time, when the AT power supply mode is adopted, the power supply facilities are numerous and scattered, being unsuitable for management, and the power supply structure is complicated, which increases the workload during operation and emergency repair. The traction power supply structure under the TRNF power supply mode is simple, convenient for maintenance, and highly reliable. Therefore, the TRNF power supply mode was selected. In the direct power supply mode, the rated operating voltage of the catenary was 25 kV, and the maximum allowable voltage was 29 kV. In the simulation process, the voltage applied by the insulator high-voltage end fittings was set as a single-phase AC peak voltage of $29\times\sqrt{2}\approx41$ kV, and the low-voltage end fittings were 0 kV. The established two-dimensional insulator model was meshed, and the electric field intensity was calculated to obtain the electric field mode vector.

4 Simulation analysis

4.1 Surface electric field of polluted insulators under dry conditions

The insulation performance of insulators under dry and wet conditions was significantly different. Fig. 3 shows the two-dimensional model and meshing diagram of the surface inorganic salt overlaying the insulator during drying, and the parameters of each pollution component are set as listed in Tab. 3. Fig. 4 shows the electric field distribution diagram on the surface of an insulator under inorganic salt deposition through a simulation calculation.

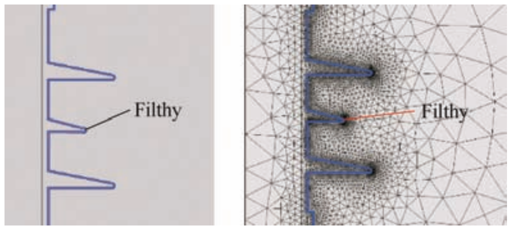

Fig. 3 Insulator surface dry pollution model

Tab. 3 Permittivity of each component

Impurity composition	$CaSO_4$	K_2SO_4	$MgSO_4$	NaCl	KNO_3	$NaNO_3$
Relative dielectric constant ε_r	1.8	5.9	8.2	6.2	5.0	5.2

In Fig. 3, the dark band on the left is a dry and dirty layer, which is evenly covered on the surface of the insulator fittings and insulating sheath, with a thickness of 1 mm. The right panel of Fig. 3 shows a two-dimensional mesh split of the insulator covered by the dry and dirty layer. Free triangles are used to mesh the graphics and refined the dirty layer and the grid around the dirty layer, making the result more accurate and reducing errors.

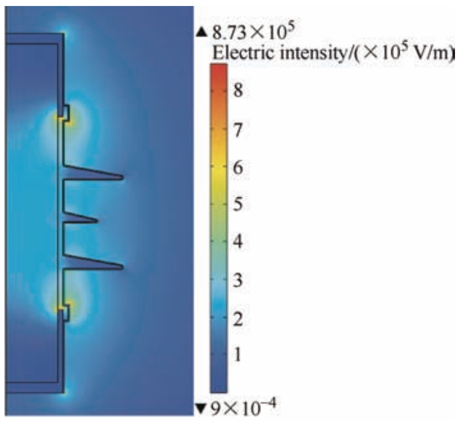

Fig. 4 Electric field distribution on the insulator surface under dry conditions

By changing the composition of the pollution layer on the insulator surface, simulations can be used to obtain the electric field intensity distribution on the insulator surface under different components, as shown in Fig. 5. As can be seen from Fig. 5, the electric field intensity of part of the insulator covered with inorganic salt changes significantly in the surface area under dry conditions. The effects of various pollutants on the surface electric field intensity follow the trend $CaSO_4$>KNO_3>$NaNO_3$>K_2SO_4>NaCl>$MgSO_4$. That is, when the insulator surface pollution layer is $CaSO_4$, the surface electric field intensity is at its maximum, while for KNO_3, $NaNO_3$, K_2SO_4, NaCl, and $MgSO_4$, the corresponding electric field intensity decreases in turn.

The influence on the electric field intensity is mainly related to the different dielectric constants of each solid pollutant during drying. $CaSO_4$ (see Tab. 3) is a nonpolar substance, and all other substances are polar substances. For nonpolar materials, electron deflection does not occur because of their nonpolar properties under an applied electric field. In an electric field, neutral molecules are easily affected by the electric field force to produce an electric dipole moment, which exhibits a charged property as viewed from the outside, resulting in external electrical manifestation. According to the definition of the relative dielectric constant, $\varepsilon_r = E_0 / E$, where the electric field in the dielectric is $E = E_0 - E'$ and E is the electric field established by the polarization charge in a polar substance. Therefore, as ε_r increases, E' increases, and the electric field E in the dielectric decreases.

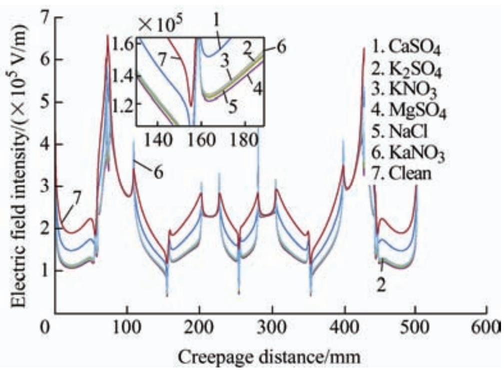

Fig. 5 Electric field distribution of each contaminant on the insulator surface under dry conditions

4.2 Surface electric field of fouled insulators under wet conditions

The dry and wet conditions of insulator surface contamination have different effects on insulator insulation performance. When inorganic salts are polluted by moisture, they dissolve and form an electrolyte solution, which forms an ion channel on the surface of the solution, increases the surface conductivity of the insulator, increases the surface leakage current, and reduces the electrical performance of the insulator. Composite insulators have excellent water-repellent properties, which can reduce water adhesion and maintain good insulation properties. However, after running for many years in the natural environment, insulators will gradually lose their hydrophobicity owing to the intervention of external factors, which will affect their normal working state. To study the influence of contamination of different components on the surface electric field of an insulator when exposed to moisture, and by considering the hydrophobic characteristics of composite insulators, a discontinuous water film can be easily formed on the surface of an insulator. A two-dimensional insulator contamination model under wet conditions was established, as shown in Fig. 6. In Ref. [19], the hydrophobic migration characteristics of silicone rubber insulators with different ash density stains was investigated through experiments and it was found that hydrophobic migration would occur on the surface of insulators with different ash density components. Therefore, the boundary material of the water film surface was set as silicone rubber when the pollution model was established to reflect the effect of hydrophobic mobility on the surface electric field.

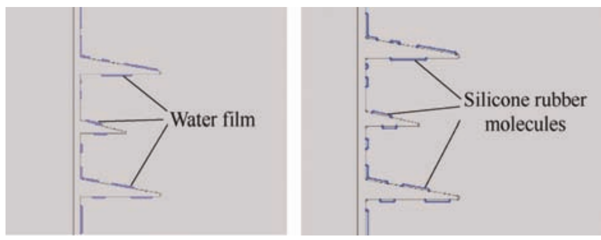

Fig. 6 Surface fouling model of the insulator under wet conditions

As shown in Fig. 6, because of the hydrophobic nature of the surface of the silicone rubber insulator, the water droplets attached to the surface of the insulator cannot be connected to form a continuous water film but are divided into multiple water films of different shapes and sizes. The intermittent dark belt-shaped part on the left is a discontinuous water film. Because the water film on the surface of the fittings is not hydrophobic, the water film is set as a continuous belt. The right picture shows that, as a result of the hydrophobic migration of the silicone rubber material, some of the silicone rubber molecules float to the surface of the dirty layer, making the surface of the dirty layer hydrophobic. During modeling, the material properties at the boundary between the water film and air were set to be consistent with the silicone rubber material to ensure that the surface of the dirty layer is hydrophobic. The dark lines in the figure represent the silicone rubber molecules on the surface of the water film.

4.2.1 Surface electric fields of insulators with pollution caused by different pollution components

According to Huang et al. [20], the surface water content of composite insulators is related to surface ash density, on the premise that the density of soluble salt deposits on the insulator surface is 0.09 mg/cm^2; when the ash density was 0.3 mg/cm^2, the pollution can reach saturation dissolution. The saturated salt solution parameters of each pollutant component were set as given in Tab. 4. The relative dielectric constant of each solution was about 79, and the surface electric field of the polluted insulator in the constant-current field was studied and calculated. It was found that the relative dielectric constant of the pollution has little influence on the electric field and does not affect the electric field distribution in the constant-current field.

Tab. 4 Electrical conductivity of solutions with different pollution components

Impurity composition	Saturation solubility S/(g/100 g)	Conductivity of solution at saturation σ/(S/m)	Temperature T/℃
NaCl	36	21.51	18
$NaNO_3$	87.6	16.06	18
K_2SO_4	11.1	4.58	18
KNO_3	31.6	16.25	18
$MgSO_4$	33.7	2.63	18
$ZnSO_4$	53.8	4.44	18
$CaSO_4$	0.255	5.6×10^{-4}	18

The electric field contour distribution when the sodium chloride solution adheres to the surface of the insulator is shown in Fig. 7.

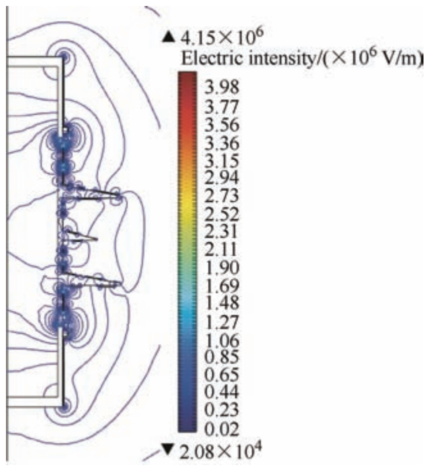

Fig. 7 Surface electric field contour map of an insulator covered by wet contamination

As shown in Fig. 7, the distribution of electric field lines is denser when the water film on the surface of the insulator is covered, indicating that the polluted solution has a greater influence on the electric field distribution. A two-dimensional section line was constructed in the model, and the spatial electric field at the section line was obtained through calculation. The electric field intensity on the surface of insulators covered by different types of pollution is shown in Fig. 8.

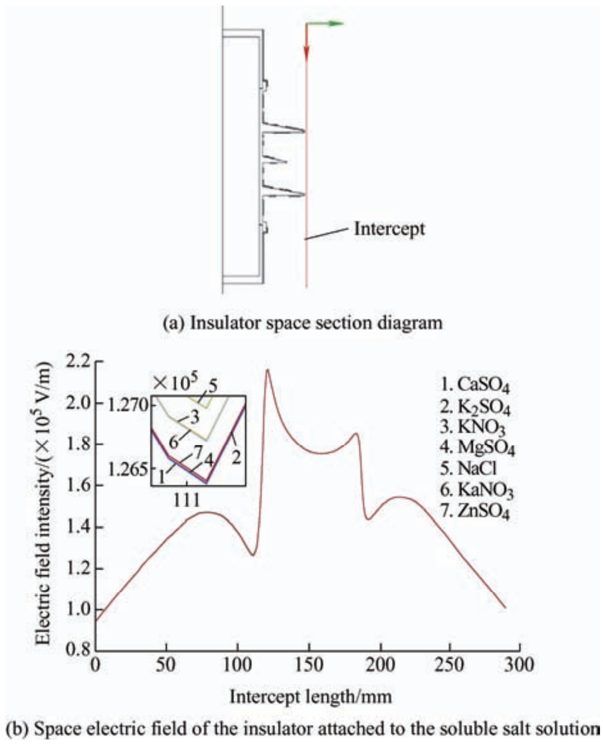

Fig. 8 Influence of wetting pollution on the surface electric field of the insulator

According to the analysis of Fig. 8, different components of moisture pollution have different effects on the surface electric field of insulators. The surface electric field intensity corresponding to NaCl was the highest, followed by KNO_3, $NaNO_3$, K_2SO_4, $ZnSO_4$, $MgSO_4$, and $CaSO_4$. It can be seen that sodium chloride, which is commonly used at present, has a greater influence on the surface electric field intensity of insulators, followed by nitrate, which has little difference, and sulfate, which has the least influence on the electric field. Through observation, it was found that this phenomenon has a greater correlation with the conductivity of each salt. As can be seen from Tab. 4, the trend in conductivity of each component was $NaCl>KNO_3>NaNO_3>K_2SO_4>ZnSO_4>MgSO_4>CaSO_4$. This indicates that the main factor determining the electric field intensity in an electric field is the conductivity of the solution. When a strong electrolyte solution meets the action of an electric field, the electrolyte ions in the solution move directly under the action of an electric field, thus forming a current. The higher the conductivity of the solution, the more freely ions move in the solution, the better the conductivity, and the greater the intensity of the electric field.

4.2.2 Surface electric field of an insulator covered by a salt mixture

The equivalent salt density method was used to measure the degree of pollution of the insulator surface, and the equivalent salt density of the insulator surface was 0.09 mg/cm^2. When hydrophobicity was good, the surface water content of the insulator per square centimeter was 17 mg, the solubility of sodium chloride was 0.5%, and the conductivity of the water film was 0.92 S/m. In contrast, when hydrophobicity was lost, these values were 11 mg, the solubility of sodium chloride 0.8%, and 1.44 S/m, respectively [20]. The surface electric field distribution of the insulator is shown in Fig. 9 after the simulation calculation.

As shown in the figure, the electric field intensity on the surface of the insulator after the loss of hydrophobicity became slightly greater than that before the loss of hydrophobicity, which is related to the saturation water content on the surface of the insulator. Before hydrophobicity loss, the contact angle between the water droplets on the surface of the insulator and the rubber surface was larger, the water droplets were fuller, and the water content was greater, which led to a decrease in the dissolved concentration of the salt solution and a decrease in the electrical conductivity.

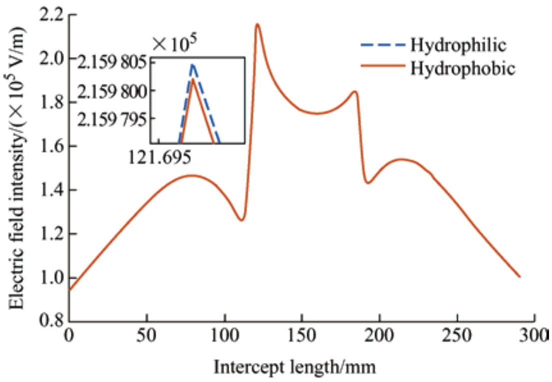

Fig. 9 Effect of hydrophobicity on the surface electric field of the insulator

After the loss of hydrophobicity, the contact angle between the water droplets and the insulator surface decreased, the water droplets flattened, and the water volume decreased, leading to an increase in the salt solution concentration and a corresponding increase in the electrical conductivity. However, the difference was small, being related to the small difference in conductivity between the two states. In addition to the mixing of different pollution components, the surface electric field distribution of the insulator under the mixing state of dry pollution and wet pollution was also considered, and a pollution adhesion model was established, as shown in Fig. 10.

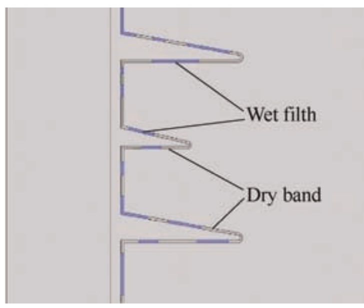

Fig. 10 Mixed pollution attachment model

Each component parameter was added to the pollution in the dry and wet states in the model, and the surface electric field of the insulator when different pollution components were attached was obtained. The surface electric field was analyzed, and the results are shown in Fig. 11. It can be seen from the figure that, when different types of pollution are attached to the surface of the insulator, whether dry or wet, the influence of the pollution component on the electric field still follows the previous conclusions. This demonstrates that the main factors that affect the electric field distribution are the dielectric constant of the dry substance and the conductivity of the wet liquid. The contamination of different states does not change when mixed.

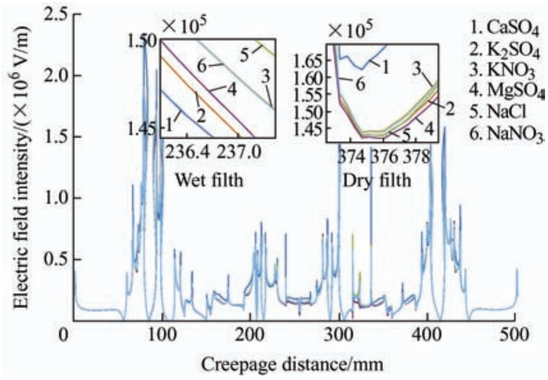

Fig. 11 Surface electric fields of insulators attached to various types of pollution under different states

4.3 Verification of conclusions

Li [21] conducted tests on the flashover voltages of insulators attached to different pollution components and obtained the electrical conductivity of each pollution solution and the flashover voltage gradient of insulators attached to different pollution components, as shown in Fig. 12 and Fig. 13, respectively.

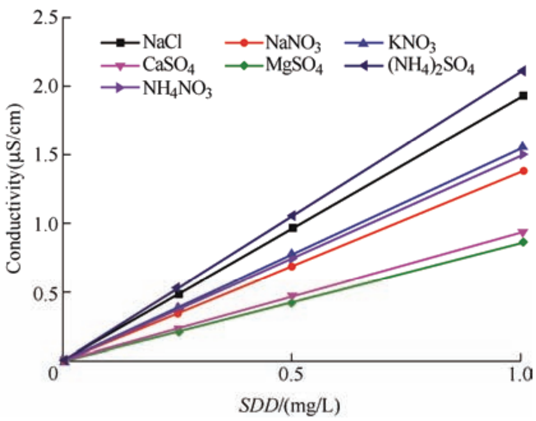

Fig. 12 Relationship between conductivity and mass concentration of soluble matter

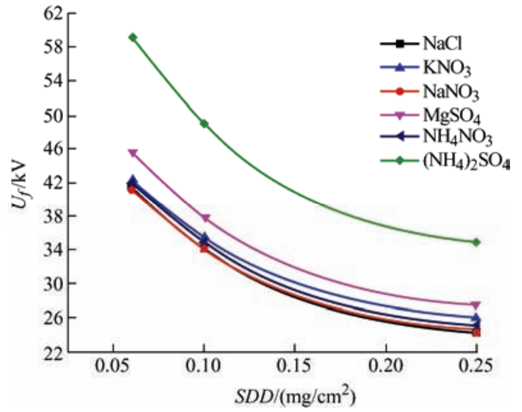

Fig. 13 Relationship between different soluble salt flashover voltage gradients and equivalent salt density

It can be seen from the figure that, under the same equivalent salt density, sodium chloride has the lowest flashover voltage gradient, followed by nitrate, and finally sulfate, while calcium sulfate has the highest flashover voltage gradient. The main reason for this difference is that the conductivities of the solutions are different. The conductivity of sodium chloride was higher than that of nitrate and sulfate at the same mass concentration. The surface potential of the insulators with different contamination levels was simulated, and the results are shown in Fig. 14.

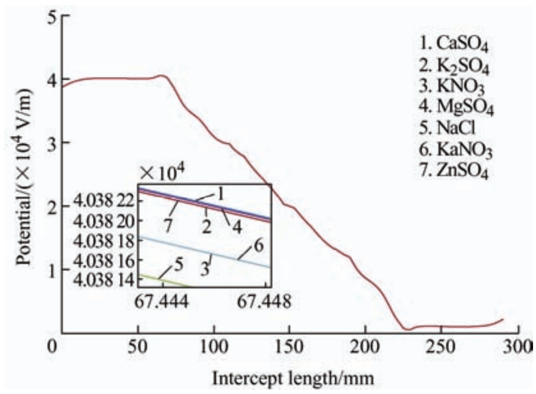

Fig. 14 Surface potential distribution of soluble salt

It can be seen from the figure that the surface potential of the insulators attached to each type of pollution has a certain difference. Among them, the potential corresponding to sodium chloride was the lowest, and the potential corresponding to calcium sulfate was the highest. The insulator potential data at a 146.4 mm section length were extracted, and the insulator potential with different types of contamination was obtained, as given in Tab. 5.

Tab. 5 Surface potential of insulator covered by soluble salt

X/mm	*Y*(potential)/V	Pollution components
146.4	20 161.872 215 869 24	$CaSO_4$
146.4	20 161.411 278 964 90	$MgSO_4$
146.4	20 160.533 318 277 60	$ZnSO_4$
146.4	20 160.457 144 952 80	K_2SO_4
146.4	20 144.562 150 853 30	$NaNO_3$
146.4	20 144.412 027 728 90	KNO_3
146.4	20 131.039 658 735 00	NaCl

According to the table, the order of potentials is $CaSO_4$> $MgSO_4$> $ZnSO_4$> K_2SO_4> $NaNO_3$> KNO_3> NaCl. This was consistent with the test results. This demonstrates that the electric field simulation results are valid and reliable and can be used as a reference for actual engineering applications.

5 Conclusions

To investigate the influence of pollution composition on the electric field distribution on an insulator surface, an insulator pollution accumulation model was established, and the surface electric field of an insulator under dry and wet conditions was simulated. The following corresponding results were obtained.

(1) Field measurements and investigations revealed that soluble salt components on the surface of the OCS composite insulator in Xining Station include $CaSO_4$, NaCl, $NaNO_3$, KNO_3, K_2SO_4, $MgSO_4$, and $ZnSO_4$. Among them, calcium sulfate accounted for the largest proportion, reaching 39.5%, while sodium chloride only accounted for 14.2%, and zinc sulfate accounted for the least, only 0.6%.

(2) A two-dimensional insulator model was established to simulate the surface electric field of an insulator covered by dry and wet pollution. It was found that the surface electric field intensity exhibited significant differences under the two conditions. The influence of the soluble salt composition on the surface electric field intensity under dry pollution was in the order of $CaSO_4$> KNO_3>$NaNO_3$>K_2SO_4>NaCl> $MgSO_4$; when the surface of the insulator was exposed to wet pollution, the trend was NaCl>KNO_3>$NaNO_3$> K_2SO_4>$ZnSO_4$>$MgSO_4$>$CaSO_4$. The simulation results were compared with the experimental results in the existing literature, and the accuracy of the simulation results was verified. These results are reliable for practical engineering applications.

(3) The presence or absence of hydrophobicity also affects the surface electric field intensity of an insulator. The main reason is that hydrophobicity affects the maximum water content on the surface of the insulator, leading to changes in the mass concentration of the soluble salt, changing the conductivity of the liquid attached to the surface, and thus affecting the electric field distribution on its surface.

(4) When dry and wet pollution jointly cover the surface of an insulator, the main factors affecting the electric field distribution on its surface still depend on the dielectric constant of dry pollution and the conductivity of wet pollution, leading to changes in the local electric field of the insulator when the pollution state changes.

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