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Influence for Ambient Relative Humidity and Pollution on Infrared Detection of Zero Resistance Insulators

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Porcelain insulators play a vital role for the safety and stability operations of electric systems. In a strong electric field, these insulators easily break down and become zero resistance insulators, which impacts the safety and stability operations of an electric system. As a result, a three-dimensional zero resistance insulator model is set up based on COMSOL. To proceed, first, we studied the voltage and current density law of insulator string when ambient relative humidity, pollution degree, and pollution salt composition are different. Then, the insulator infrared detection test is carried out in an artificial fog chamber. Results showed that the zero resistance insulator has the greatest influence on voltage when it is at a high voltage terminal, and it has the least influence on voltage when it is in the middle position. As the relative range between non-adjacent insulators and zero resistance insulators increases, the implications for a zero resistance insulator on adjacent position insulators will decrease continuously. Farther is the range between different positions on the insulators and the center axis of rotation and lower is the current density and temperature rise. The overall temperature rise of the insulator string gradually increases due to the increase in the relative humidity and pollution degree of the environment. Finally, the results indicate that the temperature difference between zero resistance insulators and other insulators gradually increases and can provide support for the infrared detection of zero resistance insulators.

Keywords: zero resistance insulator, ambient relative humidity, dirty degree, dirty salt content, infrared detection

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1 INTRODUCTION

Insulation and mechanical properties of porcelain insulators decline and deteriorate due to long-term operations in the outdoor environment, which contains mechanical and electrical loads, air pollution, cold and heat changes, and other effects. Under the action of a strong electric field, insulators are easily broken down and then transform into zero resistance insulators, which will lead to disconnection accidents and impact the safety and stability operation of the electric system (Liu et al., 2018; Yuan et al., 2018).

Zhang et al. (2018) studied the implications of humidity on the deterioration string with zero resistance through experiments. It shows that the voltage of the contaminated insulator string is greatly influenced by humidity. Humidity raise will reduce the asymmetry of the insulator string's voltage which is beneficial for the detection of zero resistance insulators. However, it is not conducive to detection while the humidity is overly high, which will easily lead to misjudgment. Xu et al. (2011) proposed a modeling simplification and calculation optimization scheme based on the electric field type, unit, area, and other factors by calculating

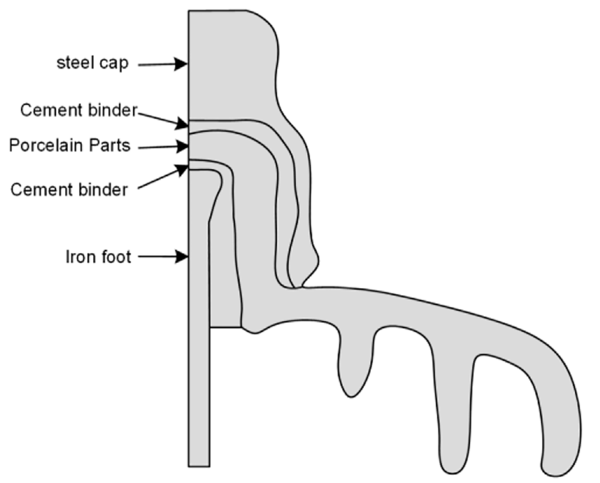


FIGURE 1 | Two-dimensional axisymmetric section of insulators.

the electric field distribution of 110 kV porcelain pillar insulators under different surface states, such as pollution and ice coating. Ilha et al. (2015) and Ilha et al. (2012) used graphite powder and epoxy resin to simulate the potential distribution of insulator strings with different pollution conductivities. By combining the experimental data with the numerical results, it is found that a small contamination conductivity would change the potential and electric field of an insulator string.

Chen et al. (2015) carried out the infrared temperature measurement test. Based on this fact, the zero resistance insulator is located in different positions of the insulator string, and a comparison between the filthy insulator string and the clean condition is established. The experimental results show that the thermal image has obvious changes while the insulator string is polluted and then results in zero resistance insulators. Therefore, a high-precision infrared thermal imager can be used to identify zero resistance insulators and polluted insulators in string. The test (Reddy & Nagabhushana 2003) of damp contaminated porcelain insulator string shows that the heating condition of porcelain surface, steel cap, and iron foot is different. Three cases of the iron foot, porcelain surface, and steel cap will cause a high-to-low temperature rise. According to the electromagnetic field and heat transfer theory, Vitelli et al. (2000) using Maxwell and heat transfer equation solved the surface heat distribution of porcelain insulators.

The previous research studies lack comprehensive consideration of the implications for ambient relative humidity, fouling degree, and

TABLE 1 | Various material properties.

Dielectric material	Porcelain	Cement agent	Iron steel cap	Air
Relative dielectric constant	4.7	8	$1e^{10}$	1
Specific conductance $\mu s \cdot cm^{-1}$	$2e^{-11}$	$1.7e^{-9}$	$1.2e^{11}$	$1e^{-8}$

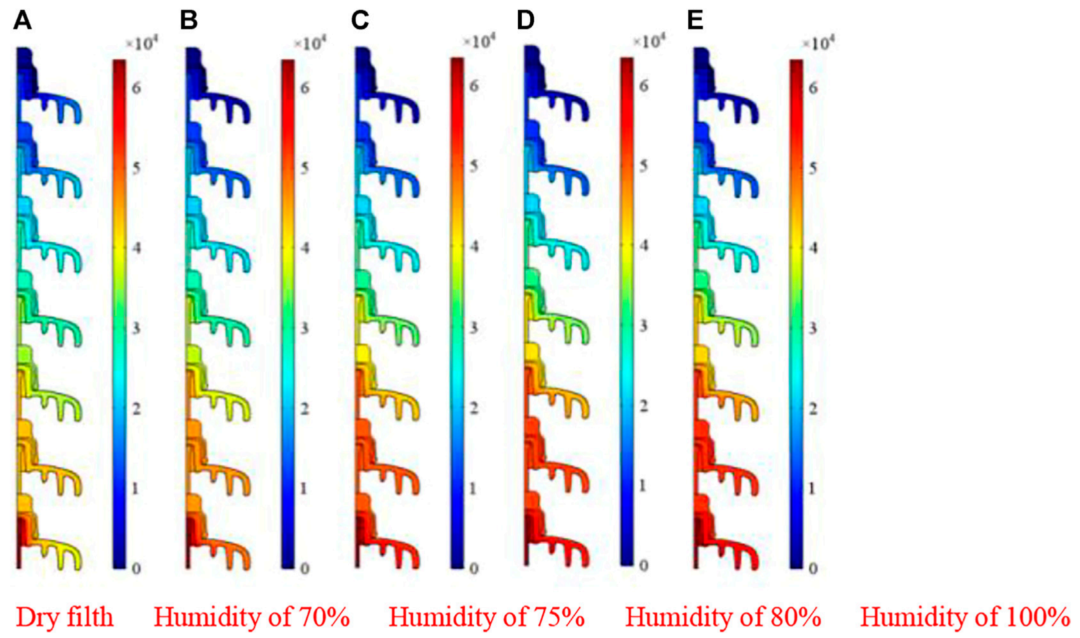


FIGURE 2 | Voltage of 2-th zero resistance insulator string as humidity raises (V). **(A)** Dry filth, **(B)** humidity of 70%, **(C)** humidity of 75%, **(D)** humidity of 80%, and **(E)** humidity of 100%.

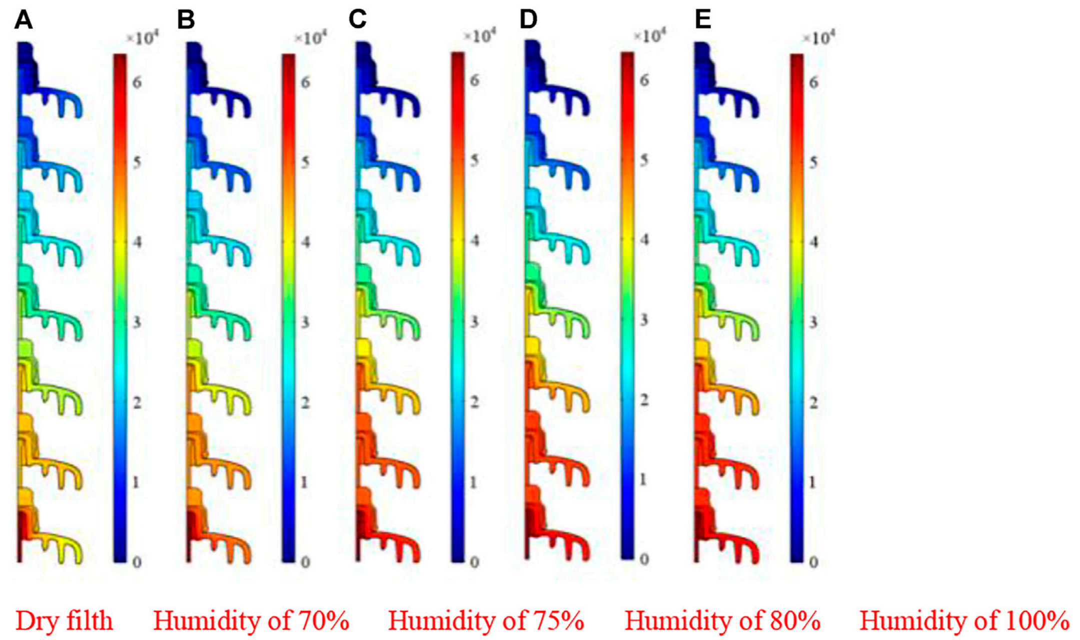


FIGURE 3 | Current density of 2-th zero resistance insulator string as humidity increases (A/m^2). **(A)** Dry filth, **(B)** humidity of 70%, **(C)** humidity of 75%, **(D)** humidity of 80%, and **(E)** humidity of 100%.

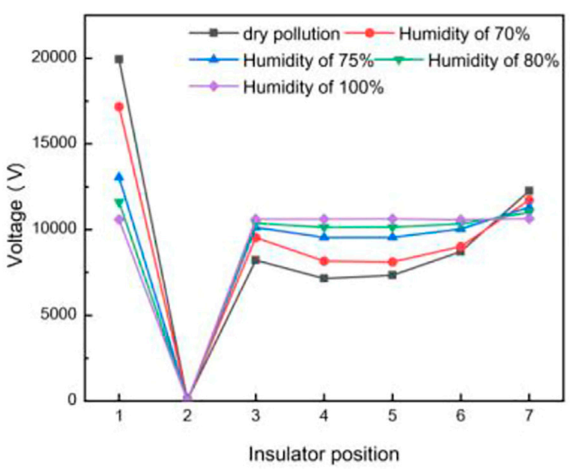


FIGURE 4 | Implications for the environmental relative humidity on voltage.

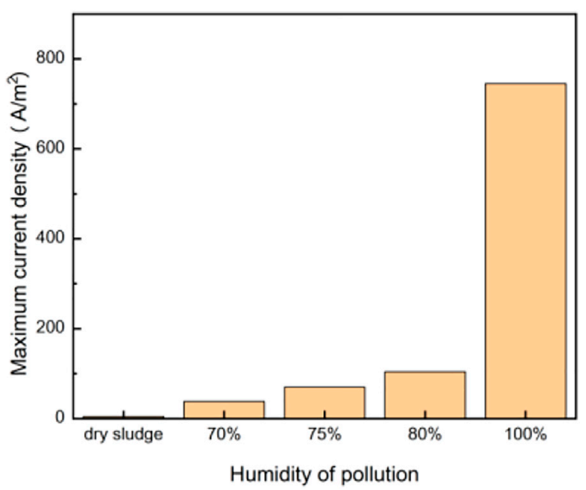


FIGURE 5 | Implications for the environmental relative humidity on the maximum current density.

fouling salt composition on the infrared detection of zero resistance insulators. Therefore, the zero resistance insulator model is set up for a more complex infrared detection environment. The effects of relative humidity and pollution on voltage and potential distribution of insulators were studied. At the same time, the infrared imaging method was used to study the heat characteristics of an insulator surface in an artificial fog chamber. The conclusion can provide further support for the research of the zero resistance insulator detection technology.

2 EMULATION MODEL OF PORCELAIN INSULATORS

The standard porcelain suspension insulators used for 110 kV line are taken as emulation objects to conduct full-scale modeling, and a simplified two-dimensional axisymmetric model of porcelain insulators is established, as shown in **Figure 1**.

Table 1 shows the material properties of the relative permittivity and conductivity of density of each insulator's

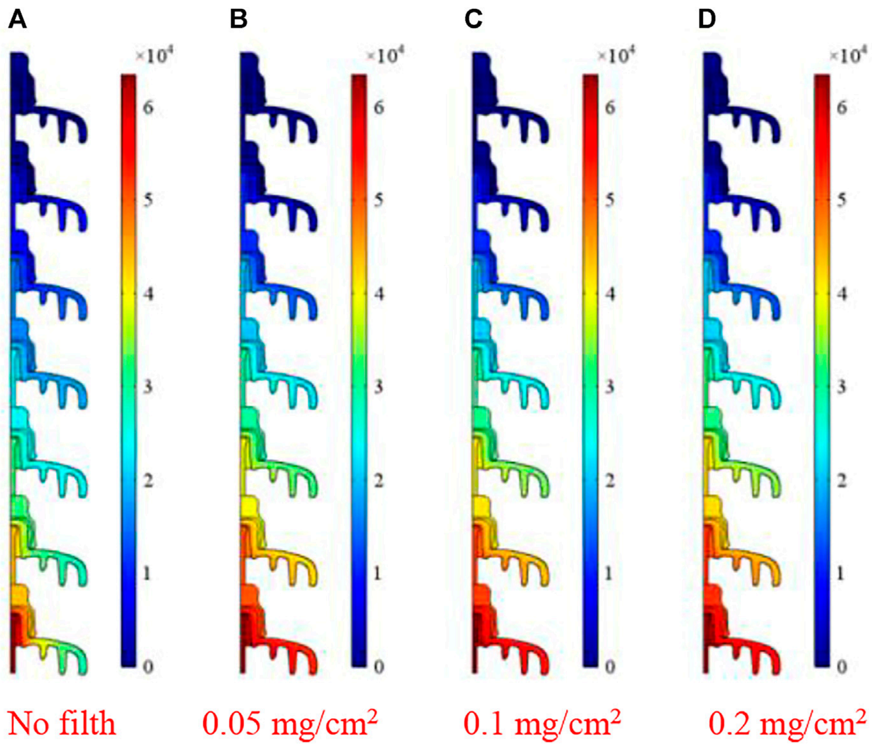


FIGURE 6 | Voltage under different pollution degrees (case of NaCl). **(A)** No filth, **(B)** 0.05 mg/cm^2, **(C)** 0.1 mg/cm^2, and **(D)** 0.2 mg/cm^2.

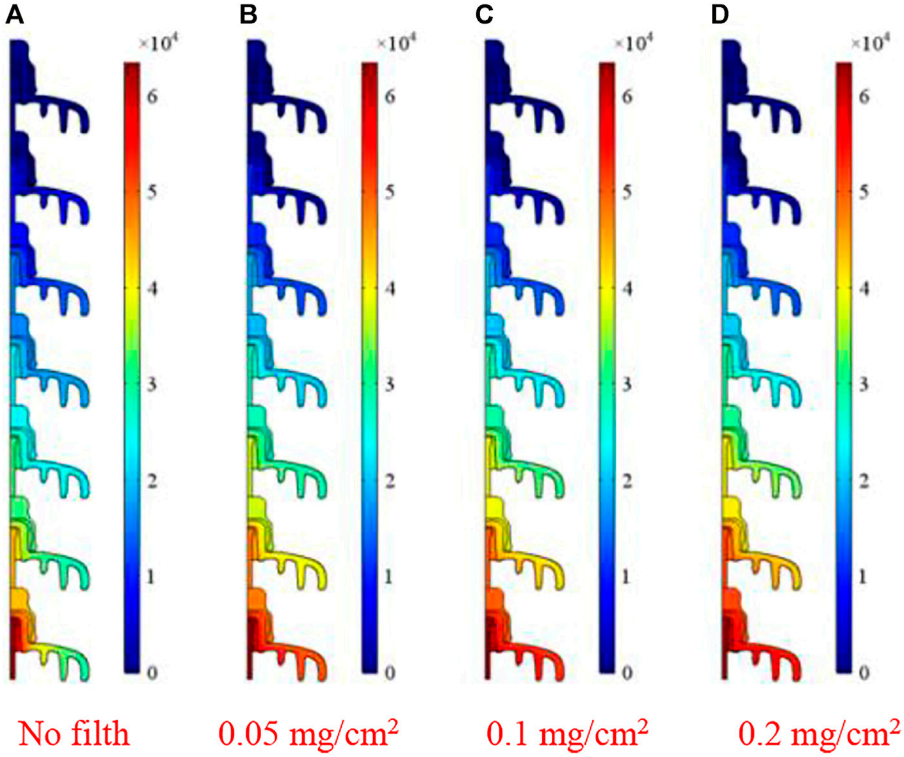


FIGURE 7 | Voltage under different pollution degrees (case of salt-mixture). **(A)** No filth, **(B)** 0.05 mg/cm^2, **(C)** 0.1 mg/cm^2, and **(D)** 0.2 mg/cm^2.

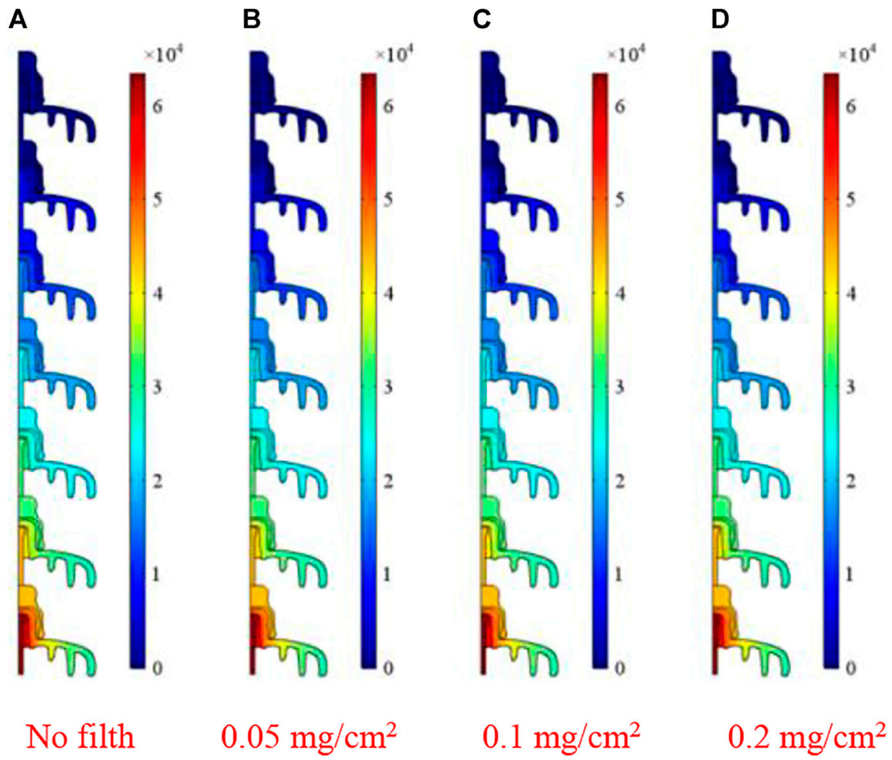


FIGURE 8 | Voltage under different pollution degrees (case of $CaSO_4$). **(A)** No filth, **(B)** 0.05 mg/cm^2, **(C)** 0.1 mg/cm^2, and **(D)** 0.2 mg/cm^2.

part. In the emulation calculation, the applied voltage of the high end of the insulator string is 63.5 kV, the applied voltage of the low end is 0 kV, and the frequency domain is 50 Hz.

The calculation formula used to convert the equivalent relation between the conductivity value of the dirty layer on the insulator surface at saturation and wetting and the salt density and gray density on the surface cover is defined by Yuan (2008). The conductivity of the dirty layer can be obtained through the conversion relationship between the experimental results obtained in Mei et al. (2014) and the conditions of different salt types and relative humidity[12–17].

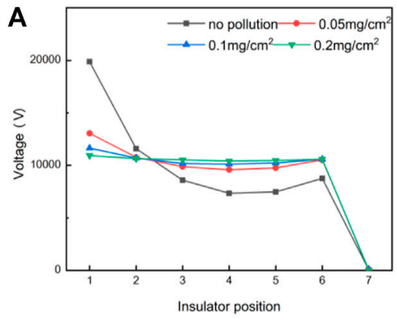
3 ELECTRIC FIELD EMULATION RESULTS AND ANALYSIS

The insulators are numbered by positions 1–7 from the high voltage terminal to the grounding end, while the 2-nd, 4-th, and 7-th are selected as zero resistance insulators in the emulation calculation.

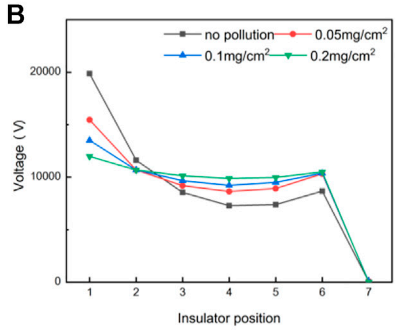
3.1 Implications for Ambient Relative Humidity on the Electric Field of Polluted Insulator String Containing Zero Resistance

The 2-th insulators are selected as zero resistance insulators with the pollution of NaCl(0.1 mg/cm^2). **Figure 2** and **Figure 3** show the emulation calculation results of voltage and current density of polluted insulator string, while the ambient relative humidity gradually rises, respectively. As the environment's relative humidity raises from 0% to 100%, the voltage of each other insulators tends to be equal, while the pollution condition of the zero resistance insulator string is constant. Meanwhile, the current density also changes with the change in ambient humidity. As the relative humidity value raises gradually, the current density value of each position in the insulator string also raises gradually.

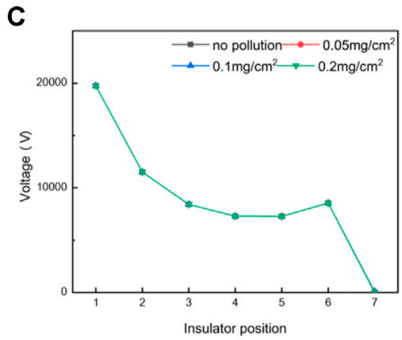
Figure 4 shows the voltage of the insulator string that presents an obvious uniform distribution as the pollution changes from dry to 100% ambient relative humidity, which indicates that the dirty layer conductivity gradually becomes the dominant factor of the dirty insulator string voltage. Ilha et al. (2015) and Ilha et al. (2012) found that the surface voltage would not change, while the conductivity of the polluted layer is greater than the critical value 5 μs cm^{-1}. The dirty layer's conductivity is 0.22 μs cm^{-1}, while the relative humidity is 70%. The voltage is unevenly distributed. The conductivity of the polluted layer is 23 μs cm^{-1}, while the relative humidity reaches 100%. **Figure 5** shows that the maximum current density raises significantly while the pollution changes from dry to the ambient relative humidity reaching 100%. Under the same pollution degree conditions, the conductivity of the surface pollution layer will increase exponentially with the rise in relative humidity, which will cause the current density at each position in the insulator string to raise nonlinearly with the raise of ambient relative humidity.



The voltage changes with fouling degree under fouling of NaCl



The voltage varies with fouling degree under fouling of salt-mixture(40%NaCl and 60% $CaSO_4$)



Voltage changes with fouling degree under fouling of $CaSO_4$

FIGURE 9 | Voltage of insulator surface containing different pollution salts under different degrees and types of pollution. **(A)** Voltage changes with the fouling degree under the fouling of NaCl. **(B)** Voltage varies with the fouling degree under the fouling of salt mixture (40%NaCl and 60% $CaSO_4$). **(C)** Voltage changes with the fouling degree under the fouling of $CaSO_4$.

3.2 Implications for the Pollution Degree and Pollution Salt Type on Electric Field of Pollution Containing Zero Resistance Insulator String

The 7-th insulators are selected as zero resistance insulators. The pollution-containing salt types include only NaCl, mixed salt (40% NaCl and 60% $CaSO_4$) and only $CaSO_4$ under the case of an 80% environment relative humidity. **Figure 6**, **Figure 7**, and **Figure 8** show the emulation calculation results of the voltage of insulator string under a pollution degree of 0 mg/cm^2, 0.05 mg/cm^2, 0.1 mg/cm^2, and 0.2 mg/cm^2. The voltage tends to be uniform with the raise of the pollution degree, while the pollution types are NaCl and mixed salt (NaCl and $CaSO_4$) while the voltage will not change where the pollution layer is only $CaSO_4$.

Figure 9 shows the insulator string's voltage. The insulator surface pollution is NaCl, mixed salt (40%NaCl and 60% $CaSO_4$),

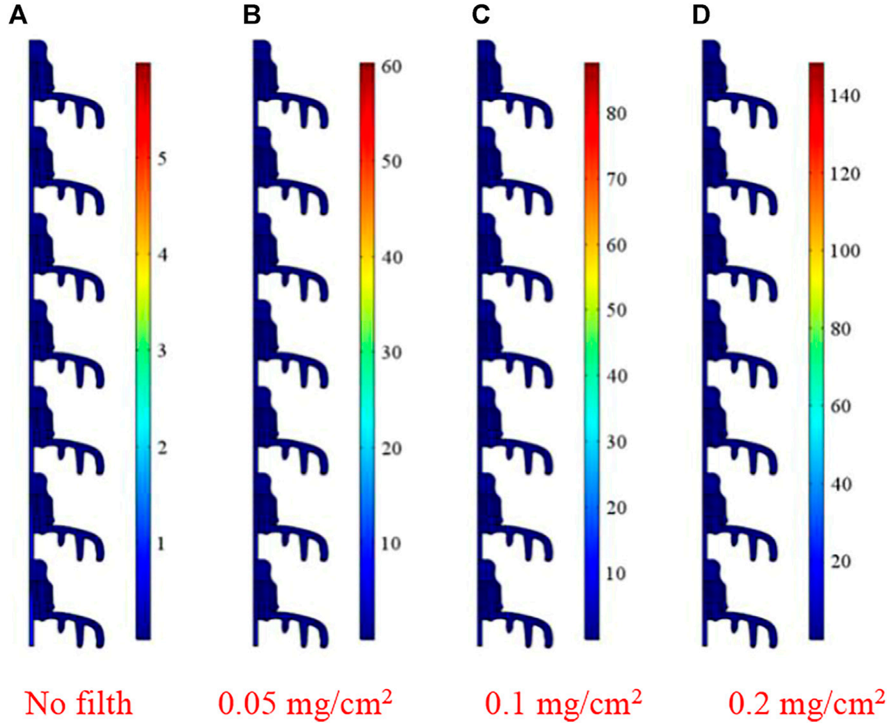


FIGURE 10 | Current density under different pollution degrees (NaCl). **(A)** No filth, **(B)** 0.05 mg/cm^2, **(C)** 0.1 mg/cm^2, and **(D)** 0.2 mg/cm^2.

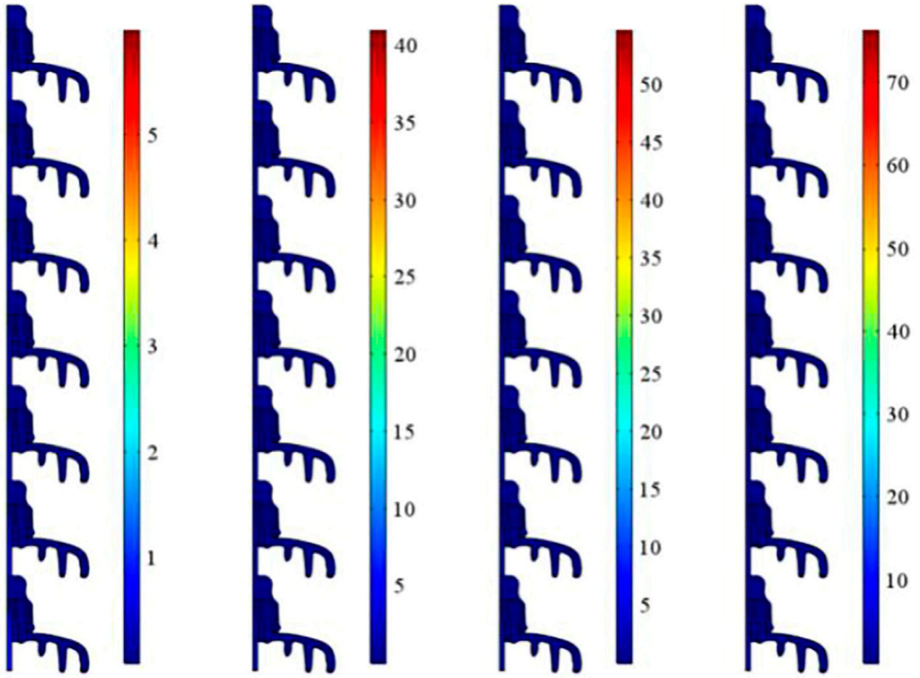


FIGURE 11 | Current density at different pollution degrees (salt mixture).

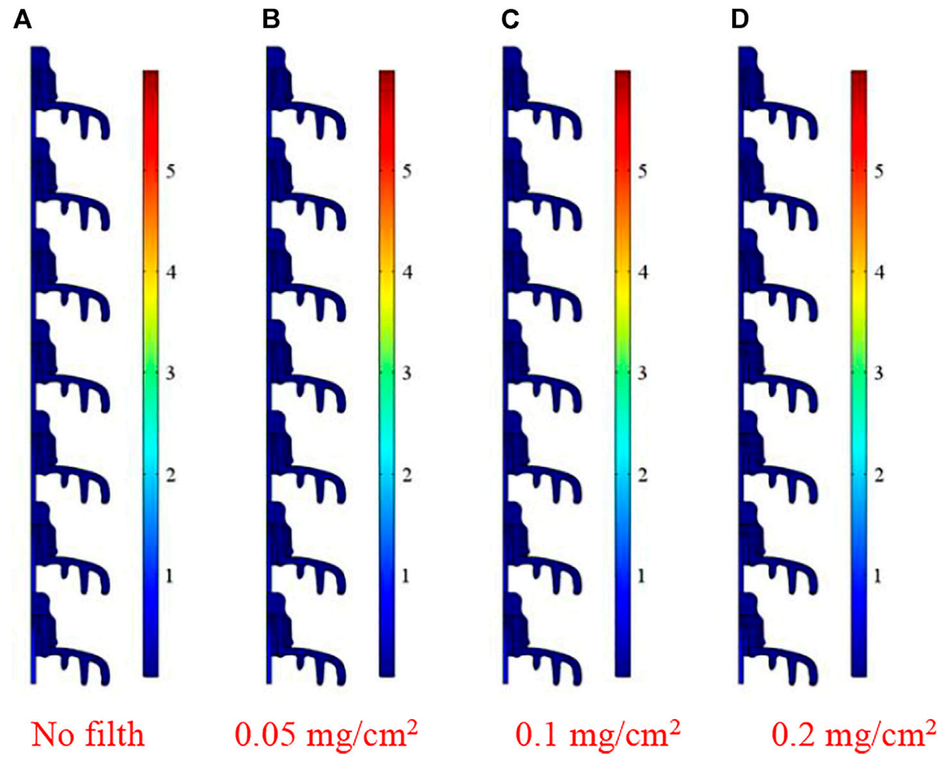


FIGURE 12 | Current density under different pollution degrees ($CaSO_4$). **(A)** No filth, **(B)** 0.05 mg/cm^2, **(C)** 0.1 mg/cm^2, and **(D)** 0.2 mg/cm^2.

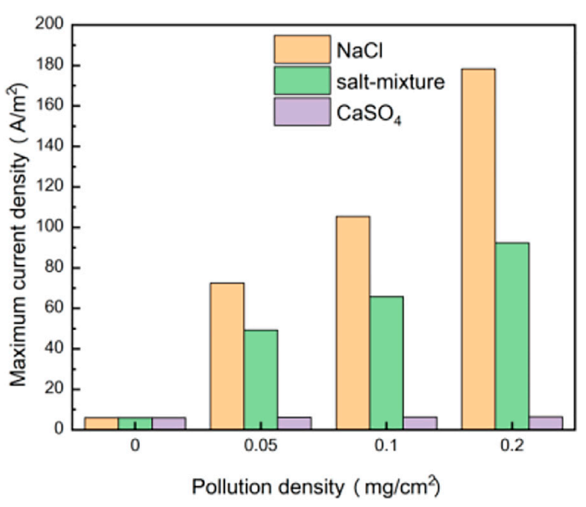


FIGURE 13 | Maximum current density of insulator surface contaminated with different types of salts.

and $CaSO_4$. The surface pollution of insulators is 0.05 mg/cm^2, 0.1 mg/cm^2, and 0.2 mg/cm^2, respectively. The voltage in the insulator string except the set zero resistance insulator tends to be uniform with the raise of the pollution degree under cases of the pollution of NaCl and mixed salt. **Figure 9A** shows that the partial voltage of non-zero resistance insulators is about 10580 V, while the pollution degree is 0.2 mg/cm^2, which is similar to the result shown in **Figure 9B**. The voltage is even in this condition. The reason is that the pollution layer's conductivity on the insulator surface is slightly greater than the critical value ($5\,\mu s\,cm^{-1}$), while the pollution degree is 0.2 mg/cm^2; this results in the pollution layer's conductivity can no longer impact the voltage of the insulator string. **Figure 9C** shows that the voltage is not uniform and will not change with the change of the surface pollution degree under cases of the pollution of $CaSO_4$.

Figure 10, **Figure 11**, and **Figure 12** show that the current density at all insulator string increases gradually with the raise of insulator surface pollution degree, while the pollution layer is NaCl or mixed salt. The current density in the insulator string does not change with the rise in the pollution degree under the case of the pollution of only CaSO4.

Figure 13 shows the maximum current density of different pollution degrees and salt types under the ambient relative humidity of 80%. The pollution type contains only NaCl, the mixed salt of NaCl, and only $CaSO_4$ with the pollution degree of $0mg/cm^2$, $0.05mg/cm^2$, $0.1mg/cm^2$, and $0.2mg/cm^2$. An increase in the pollution degree of salts with high solubilities, such as NaCl, covering the insulator surface will highly increase the maximum current density. This is the reason that the salt content with a high solubility per unit area is defined as pollution. Under the same voltage, the maximum

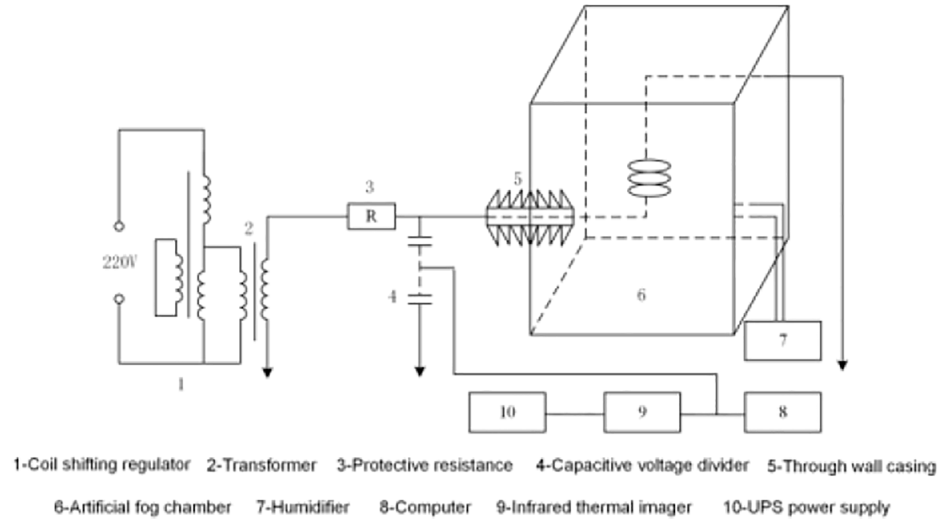


FIGURE 14 | Schematic diagram of the test.

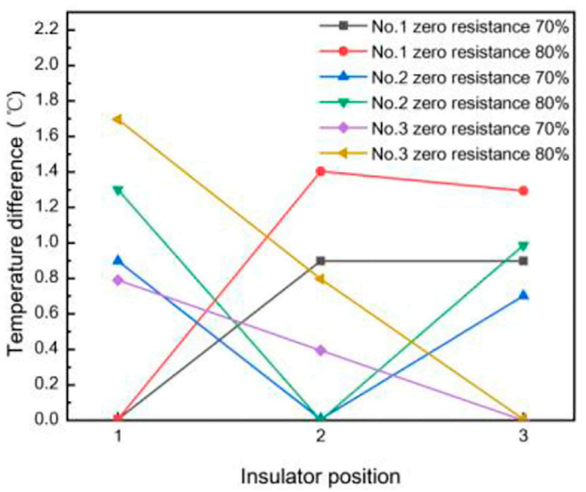


FIGURE 15 | Temperature difference between zero resistance insulators and the others under a relative humidity of polluted string of 70% and 80%.

current density raises with the raise of the conductivity of the polluted layer. However, due to the low solubility of some salts like $CaSO_4$ when the salt content in the dirty layer has exceeded the amount of salt that can be dissolved after the dirty hygroscopicity, the maximum current density of the insulator string will not be changed by the ascent of pollution density. At this time, the conductivity of the insulator pollution layer will not rise with the rise of pollution degree but is mainly affected by the environmental relative humidity.

4 RESEARCH ON THE INFRARED DETECTION TEST OF ZERO RESISTANCE INSULATOR

4.1 Testing Apparatus

The test is carried out on the basis of GB/T4585-2004/IEC60507:1991—artificial pollution test for high voltage insulators used in AC systems" standard. **Figure 14** shows the test principle. A voltage regulator is a moving coil voltage regulator with a rated input voltage of 220 V, an output voltage of 0–250 V, and a rated capacity of 15 kV A. The protection resistance value is 10kΩ. The power supply is provided by a 10 kV A/100 kV power frequency test AC transformer. The high pressure side leads to the artificial fog chamber through the epoxy sleeve. During pressurization, voltage shall be rapidly boosted to the test voltage by uniform boosting, and the temperature distribution diagram of the insulator string shall be shot by an FLIR T440 infrared thermal imager. Three U70BP standard porcelain suspension insulators are tested.

4.2 Test Results and Analysis

4.2.1 Heat Characteristics of Insulator String With Zero Resistance Under Different Ambient Relative Humidities

Figure 15 shows the temperature difference between zero resistance insulators and others, while the relative humidity of pollution is 70% and 80%. The temperature rise of zero resistance insulators is relatively low, which results in the temperature difference between them and other insulators to be large. With the gradual raise of relative humidity, the temperature difference also gradually becomes larger. Based

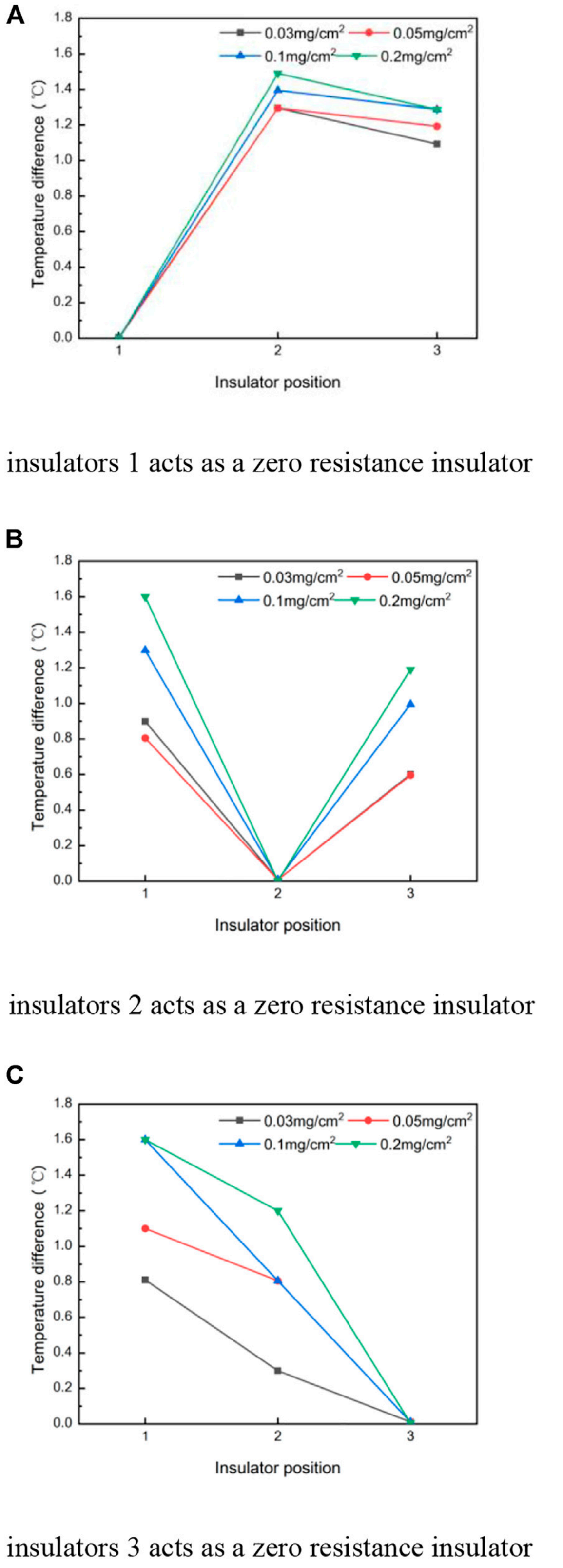


FIGURE 16 | Temperature difference between the zero resistance and other insulators in the connection position between the iron foot and the lower *(Continued)*

FIGURE 16 | surface under different pollution degrees. **(A)** Insulator 1 acts as a zero resistance insulator. **(B)** Insulator 2 acts as a zero resistance insulator. **(C)** Insulator 3 acts as a zero resistance insulator.

on different humidities or different positions of zero resistance insulators in the string, the temperature difference of insulators on the high-voltage side is greater than or equal to that of insulators on the low-voltage side.

4.2.2 Heat Characteristics of Insulator String With Zero Resistance Under Different Pollution Degrees

Figure 16 shows the temperature difference between zero resistance insulators and the others in the string with different pollution degrees at the connection position between the iron foot and the lower surface. The temperature difference between zero resistance insulator and the others will raise gradually with the raise of pollution degree (raising from 0.03 mg/cm^2 to 0.2 mg/cm^2). The insulator 1 is selected as a zero resistance insulator in the real test. The temperature rise difference of insulator 2 is 1.3°C and that of insulator 3 is 1.1°C, while the pollution degree is 0.03 mg/cm^2; The temperature rise difference of insulator 2 is 1.3°C and that of insulator 3 is 1.2°C, while the pollution degree is 0.05 mg/cm^2. The temperature rise difference of insulator 2 is 1.4°C and that of insulator three is 1.3°C, while the pollution degree is 0.1 mg/cm^2; the temperature rise difference of insulator 2 is 1.5°C and that of insulator 3 is 1.3°C, while the pollution degree is 0.2 mg/cm^2. The temperature difference between other insulators and zero resistance insulators raises with the raise of pollution degree. Although some data of temperature difference do not increase significantly, the overall raise trend is the same as the emulation results.

5 CONCLUSION

Through the three-dimensional zero-value insulator model simulation and insulator infrared detection test, the following three conclusions are drawn. The research results can provide support for the infrared detection of zero-value insulators:

(1) Zero resistance insulators have a great influence on adjacent position insulators, while the influence on other non-adjacent position insulators has a distance correlation. In other words, with the increase in the relative distance between the non-adjacent insulators and the zero resistance insulator, the influence will decrease continuously.
(2) The temperature rise at different positions on the insulators is related to the distance from its own center axis. Farther the distance from the rotation center axis is, the smaller the temperature will rise. The test shows that the maximum temperature rise occurs at the connection between the iron foot and the lower surface.

(3) With the raise of relative humidity and pollution degree, the overall temperature rise of the insulator string gradually raises. The temperature difference between zero resistance insulator and other insulators also raises gradually, but the temperature difference between adjacent non-zero resistance insulators is still small.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LC, FL, and MC conceived the idea and designed the experiments. XH, RH, and YZ led the experiments. All authors read and approved the final manuscript.

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