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An Optimized Infrared Detection Strategy for Defective Composite Insulators According to the Law of Heat Flux Propagation Considering the Environmental Factors

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ABSTRACT Composite insulators have been extensively adopted in electric transmission lines due to their preferable resistance to contamination flashover. To generally ensure the function of power networks, it is of crucial importance to perform regular online detection and the timely renewal of poor-quality insulators. As the most extensively employed method for the online analysis of composite insulators, infrared (IR) detection is defective based on the false detection rate and the high rate of undetected inner defects. Via numerical simulation and analysis and a test of the simulation model, this paper seeks to systematically ascertain how the defect temperature and IR results are related to each other for different types of conditional thermal defects in composite insulators, especially the relationship between humidity and heating. Finally, considering our previous findings and the on-site feasibility of the methods, some suggestions for IR detection methods regarding composite insulators are proposed. The findings of this paper are conducive to elucidating the conduction of heat flowthrough the composite insulators and reducing the false detection rate arising from moisture and inner defects. Furthermore, the optimized IR detection method targeting high humidity areas can also be valuable in reference to other power supply units.

INDEX TERMS Heat flow, composite insulators, IR detection, inner defects, non-destructive detect.

I. INTRODUCTION

Composite insulators have been extensively employed in EHV and UHV transmission systems due to their light weight and preferable resistance to contamination flashover [1]– [3]. Most composite insulators have a favorable running condition, whereas fractures and other extreme faults that progressively develop from internal defects can occur in some composite insulators [4]– [6]. Based on existing operations, the failure rate would be effectively reduced and EHV transmission networks would be safer with the online and periodic sampling assessment [7], [8].

Infrared (IR) detection is one of the most frequently adopted and among the most effective detection methods [9]– [13]. The temperature distribution can be detected superficially on energized composite insulators at a long distance or within a close range using a handheld IR thermal imager. Additionally, the internal discharge fault of a composite insulator can be effectively determined in accordance with the surface temperature distribution law. Nevertheless, no international standard has been established to determine abnormal IR results for composite insulators. Chinese power supply units are primarily DL/T664-2008. When the rise in temperature of a composite insulator is greater than 0.5∼1 K, defects are deemed to exist. However, many composite insulators shows a greater temperature rise than 0.5-1 K, especially in high humidity region, the standards has not been carried strictly. In the meantime, for the most dangerous fracture failures resulting from unknown causes in composite insulators, the results indicate that an internal discharge is ongoing prior to the fracture, and power supply units abiding by the existing IR testing standards fail to detect these defective insulators; several fracture failures remain after periodic IR detection [4], [5].

To improve the existing IR detection methods, in light of a systematic study of the relationship between internal defects and IR temperature measurements for conditional thermal defects of insulators, the conduction characteristics of heat flow in an insulator and the influencing factors were studied in this paper. First and foremost, a conduction model of heat flow was established in the composite insulator factoring in the thermal defects to qualitatively determine how the defect temperature and IR measurement results relate. Second, the distribution of the surface temperature field was attained by adopting a finite element simulation, and the theoretically calculated results were verified using artificial defect tests. Third, the impact exerted by common environmental factors on the IR temperature measurement results was studied. Finally, in accordance with the simulation and test results, some suggestions were proposed to improve the existing IR measurement methods.

II. THEORY AND SIMULATION

A. THEORETICAL MODELING ANALYSIS

Several processes, including internal partial discharge, external corona discharge, surface resistivity reduction and the polarization of polar materials, can induce a local temperature increase in composite insulators [14]– [16]. However, the decrease in resistivity arising from surface contamination or moisture and polarization heating does not negatively affect the primary performance of composite insulators in the short term, and external coronas can be distinguished using ultraviolet (UV) methods [16]. Therefore, the IR anomalies resulting from a partial discharge in the air gap will be stressed.

A polar coordinate system was established to describe the heat flow conduction in a composite insulator (as exhibited in Fig. 1). The core and the silicone rubber sheath are considered homogeneous materials; the radius of the core is r_1, and the thickness of the sheath is $r_2 - r_1$. The environmental temperature is constant at T_0.

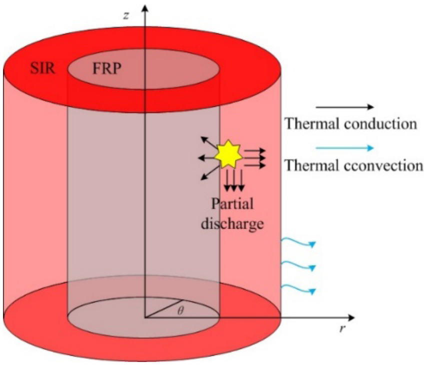


FIGURE 1. **Heat flow propagation in the composite insulator.**

At $t = 0$, a partial discharge occurs in the composite insulator, and the energy generated from the discharge is conducted in each direction to the core and to the silicone rubber in the heat conduction mode. The heat conduction process is predominately determined by the thermal conductivity coefficient of the material. The heat conduction in the silicone rubber is consistent with Eq. (1) [17].

$$C_V \frac{\partial T(t, r, \theta, z)}{\partial t} = \kappa \overrightarrow{\nabla}^2 T(t, r, \theta, z) \tag{1}$$

Where $T(t, r, \theta, z)$ is the spatio-temporal distribution of the temperature field, C_V is the heat capacity of the material per unit volume, and κ is the thermal conductivity coefficient of the material.

Since defects are generally much smaller than the overall size of an insulator, the impact on heat conduction exerted by the metal end fittings can be neglected. Heat is principally conducted during the heat transfer between silicone rubber and the air. Further, since the rise in temperature of the insulator is usually approximately dozens of K, the heat transfer process is consistent with Newton's law of cooling (Eq. (2)) [17], where k denotes the Newton coefficient of heat dissipation.

$$k\left(T|_{r=r_2} - T_0\right) = \kappa \left.\frac{\partial T}{\partial r}\right|_{r=r_2} \tag{2}$$

The heat dissipation coefficient k, which is affected by the physical state of the flowing air, the law of change in the physical state under the conditions of changing temperature and changing pressure, and the appearance of the heat dissipation surface, is generally between 1 and 10 $W^*m^{-2*}K^{-1}$. In addition, under the condition of load balance, there is little difference in the thermal radiation emitted and received by the object. Therefore, the influence of heat radiation on heat dissipation can be neglected; this statement will be proved in section II.B.

To attain the peak point in the surface temperature rise, it is crucial to simplify the equation to a certain extent. The area with the maximum surface temperature is small relative to a certain size of defect. Consequently, assuming that the defect is infinitely long along the z direction, the surface temperature rise of the insulator satisfies Eq. (3).

$$\begin{aligned} T(r, \theta) &= A_0 \ln r + C_0 + D \\ D &= B_0\theta + \sum_{n=1}^{\infty}\left(A_n r^n + B_n r^{-n}\right)\cos(n\theta + \phi_n) \end{aligned} \tag{3}$$

Where D is the uneven term stemming from the asymmetric distribution of the heat source in space. To numerically solve the temperature rise, the impact on the results that is exerted by the defect width is further neglected when the defect size substantially exceeds the maximum heating point. The attained variation in the maximum surface temperature rise with time is consistent with Eq. (4).

$$\begin{aligned} u(r, t) = {} & A_0 \ln r + C_0 \\ & + \sum_{i=1}^{\infty} C_i \begin{bmatrix} Y_1(\lambda_i r_1) J_0(\lambda_i r) - \\ J_1(\lambda_i r_1) Y_0(\lambda_i r) \end{bmatrix} e^{-\lambda_i^2 \alpha t} \end{aligned} \tag{4}$$

Where the undetermined coefficient is consistent with Eq. (5).

$$A_0 = \frac{T_0 - T}{\ln r_2 - \frac{\beta}{r_2} - \ln r_1}$$
$$C_0 = \frac{T\left(\ln r_2 - \frac{\beta}{r_2}\right) - T_0 \ln r_1}{\ln r_2 - \frac{\beta}{r_2} - \ln r_1} \tag{5}$$

The eigenvalues are consistent with Eq. (6).

$$\begin{aligned} &J_0(\lambda r_1)\, Y_0(\lambda r_2) - Y_0(\lambda r_1)\, J_0(\lambda r_2) \\ &\quad = \beta\lambda \left[J_0(\lambda r_1)\, Y_1(\lambda r_2) - Y_0(\lambda r_1)\, J_1(\lambda r_2)\right] \end{aligned}$$
$$C_i = \frac{\int_{r_1}^{r_2} v(r,0) \left[\begin{array}{l} Y_1(\lambda_i r_1)\, J_0(\lambda_i r) - \\ J_1(\lambda_i r_1)\, Y_0(\lambda_i r) \end{array}\right] rdr}{\int_{r_1}^{r_2} \left[\begin{array}{l} Y_1(\lambda_i r_1)\, J_0(\lambda_i r) - \\ J_1(\lambda_i r_1)\, Y_0(\lambda_i r) \end{array}\right]^2 rdr} \tag{6}$$

The IR temperature measurements of the composite insulators reflect the surface temperature rise in the long term after thermal equilibrium. Therefore, the steady-state solution when the time approaches infinity (Eq. (7)) is:

$$T(r,\theta) = A_0 \ln r + C_0$$
$$A_0 = \frac{T_0 - T}{\ln r_2 - \frac{\beta}{r_2} - \ln r_1}$$
$$C_0 = \frac{T\left(\ln r_2 - \frac{\beta}{r_2}\right) - T_0 \ln r_1}{\ln r_2 - \frac{\beta}{r_2} - \ln r_1} \tag{7}$$

Where β is the specific value between the silicone rubber conductivity coefficient κ and the heat dissipation coefficient k.

Normally, the heating condition of composite insulators is described by the surface temperature rise, i.e., the difference between the maximum heating point temperature and the ambient temperature. As Eq. 7 indicates, in the presence of a constant ambient temperature, the insulator surface temperature rise T_2 and the defect temperature T_1 conform to the linear relationship in Eq. (8).

$$T_2 = (T_1 - T_0)\frac{\beta}{r_2(\ln \frac{r_2}{r_1} - \frac{\beta}{r_2})} \tag{8}$$

As shown by Eq. (8), for a defect temperature that exceeds the ambient temperature, the IR temperature measurements for insulators are lower than those of the internal defects, and the temperature rise and defect temperature are linearly related to each other. Nevertheless, the size of the composite insulator, the umbrella shape and the external environment will clearly impact the heat dissipation coefficient of the insulator surface. Therefore, the IR temperature measurements can merely indicate whether the insulator is problematic, and the extent of defect deterioration cannot be judged by the value of the temperature rise. During operation and maintenance, it is impossible to compare the values for temperature rises in different regions of an insulator to eventually determine the extent of defect deterioration. Even for the same insulator, due to changes in the temperature measurement environment, a direct comparison of the temperature rise values during different periods is not relevant.

B. SIMULATION ANALYSIS

The superficial temperature field distribution of a 500 kV composite insulator was simulated using the simulation software Comsol. The sheath is 6 mm thick, and the core diameter is 24 mm. There are one large and two small umbrella structures, and the umbrella space is 81 mm. The thermal defect is a 30 mm * 5 mm * 0.5 mm cuboid in the interface between the silicone rubber and the core. In the simulation, the thermal conductivity of the silicone rubber reached 3.00 $W{*}m^{-2}{*}K^{-1}$, and the thermal conductivity of the core reached 1.46 $W{*}m^{-2}{*}K^{-1}$. Under laboratory conditions, the surface heat transfer coefficient of a 220 kV composite insulator reaches 2.414 $W{*}m^{-2}{*}K^{-1}$ [18]. We hypothesized that the value is the same for the 500 kV composite insulator (which requires verification in the following test). The ambient temperature is 20 °C. The internal defects of composite insulators comprise non-conduction defects, including air voids, as well as conduction defects, including water or a carbide channel.

Primarily, the effect of the thermal radiation process was studied. A copper defect (0.5 * 0.5 * 0.5 mm) with a temperature of 100 °C was arranged in the composite insulator model. The maximum superficial temperature was 25.7 °C, and the result slightly increased to 26.2 °C when the radiation process was neglected. The simulation results show that the convection thermal process dominated the heating process.

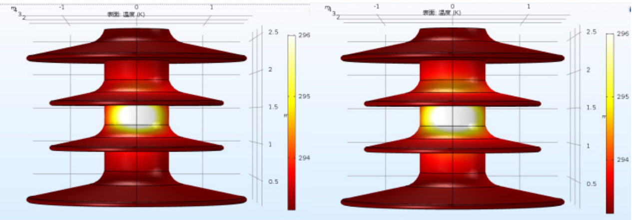


FIGURE 2. Comparison of the thermal simulation results (left: the thermal radiation process was considered; right: the thermal radiation process was neglected).

In addition, the area of heating on the outside (over 20mm) was much greater than that of internal defect (0.5mm). There was a relationship between the type of internal defect and heating area on the outside. However, the type of internal defect was comprehensive, partial discharge, polarization, conductive zone all would lead to heating. Therefore it would be difficult to use IR for size measurement. More importantly, internal defects were all intolerable for composite insulators, which should be replaced immediately when discovered, regardless of its size. Besides, the positive relation between size and level of damage would not maintain constantly, thus no standards ever provide such information. They only set regulations on the heating temperature.

For the purpose of the subsequent verification test, the conduction defects and non-conduction defects were simulated through the air and copper, respectively.

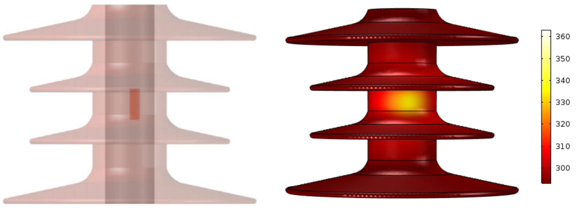


FIGURE 3. **Simulation model (left) and Results of the surface temperature field distribution (right).**

As indicated by the simulation results, the maximum surface temperature of the defective insulator occurs in the center of the defects area (as exhibited in Fig. 3), and is clearly lower than the temperature of the internal defect. The change in the external temperature with the defect temperature still consistent with a linear relationship (as exhibited in Fig. 4), which is consistent with the results of Eq. 8. Although many uneven terms resulting from asymmetric defects have been omitted in the theoretical analysis, the basic laws of the internal and external temperature rise amplitude are not affected. Furthermore, in contrast to the non-conduction defects, the heat exchange performance between the conduction defects and the sheath is better. Therefore, the difference between the internal and external temperatures is smaller.

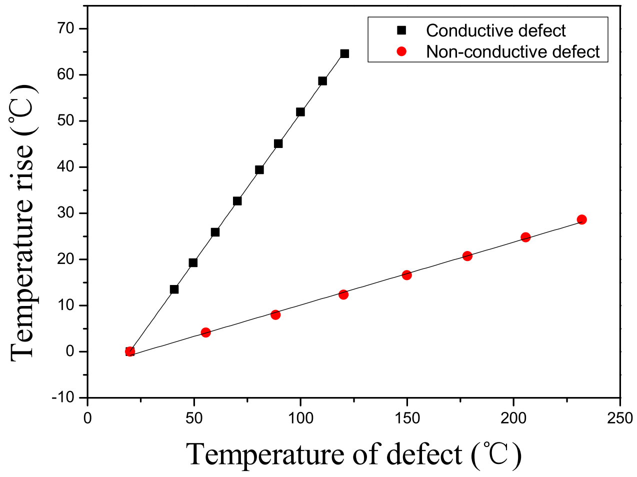
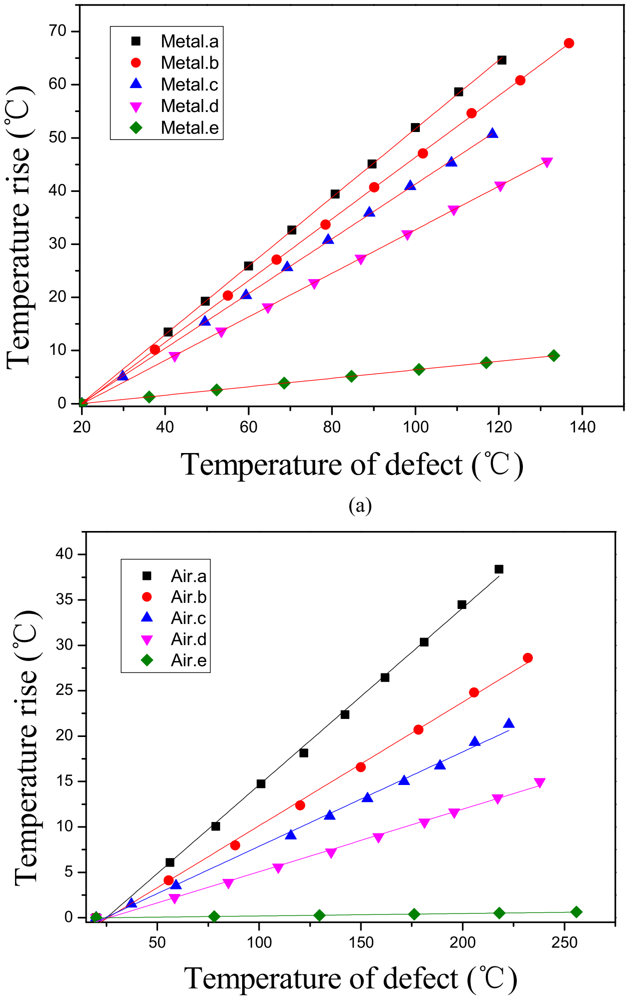


FIGURE 4. **Temperature field simulation results.**

There may be differences in the size of the internal defects of composite insulators. Therefore, the difference between the IR temperature measurement results and the actual defect temperature rise when the defect size changed was further simulated. Five different sizes were factored in:

a. 30 mm * 5 mm * 0.5 mm;
b. 15 mm * 5 mm * 0.5 mm;
c. 10 mm * 5 mm * 0.5 mm;
d. 5 mm * 5 mm * 0.5 mm;
e. 0.5 mm * 0.5 mm * 0.5 mm.



(a)

(b)

FIGURE 5. **Simulation results of the IR temperature rise for defects with different sizes. (a) Simulation results of conduction defects. (b) Simulation results of air defects.**

The results show that the defect size has a significant impact on the IR temperature measurements. A heat source with a finite size was decomposed into point heat sources. The result of the IR temperature measurement is the superposition of all the point heat sources. Small-sized defects contain fewer point sources, and their temperature rise is comparatively small. Moreover, non-conduction defects are more difficult to detect by the IR method due to the poor heat exchange property of such defects.

For a defect with a temperature of 100 °C and length and height of 5 mm and 0.5 mm, respectively, the defect length is exponentially related to the surface temperature rise. With a decrease in the defect length, the surface temperature decreases rapidly. In the presence of a large defect length, the superficial observation point with the maximum temperature is perceived to be infinitely small in contrast to the defect. Accordingly, the impact exerted by the defect size on the surface temperature rise is reduced.

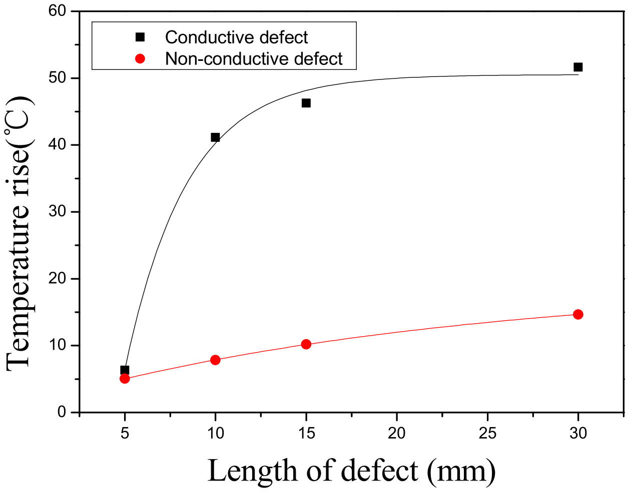


FIGURE 6. **The relationship between defect length and temperature rise at the defect temperature of 100°C.**

The IR results were dramatically affected by the location of the defects due to the shape of the umbrella. For the large copper defect (15 * 5 * 0.5 mm, 100 °C), the temperature rise was 46.43 °C when the defect was located between 2 umbrellas, while the result decreased to 4.6 °C when the defect was located just under the sheath (Fig. 7 left). The heat transfer process in the silicone rubber is obstructed by the thick umbrella. More attention should be paid to abnormal heating located near the root of the umbrella, even if the temperature rise is slight.

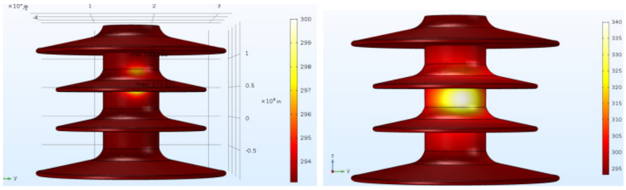


FIGURE 7. **Comparison of the thermal simulation results with different defect locations.**

III. EXPERIMENTAL RESULTS

A. SAMPLE PREPARATION AND EXPERIMENTAL SETTING

To verify the simulation results and to further study the impact exerted by environmental factors on the IR temperature measurements of an insulator with thermal defects, a thermal probe was placed in the composite insulator. To exclude the impact exerted by a possible air gap on the heat conduction process, a shallow groove was superficially created on the core and was embedded with the probe. Next, the groove was sealed with epoxy resin material (as exhibited in Fig. 8) and the umbrella and sheath is molded through injection.

To prevent the probe from being damaged by the large pressure and high temperature during injection, the temperature probe was prepared by twining the thermocouple with a manganese copper wire. The probe size is the same as the defect size employed in the simulation, which is 30 mm ∗ 5 mm ∗ 0.5 mm.

FIGURE 8. **The temperature probe embedded in the core.**

By applying DC voltage to both ends of the probe, heat can be generated. The surface temperature of the insulator was recorded with an IR thermal imager (model: FLIR SC600).

The laboratory temperature was maintained at 20 °C, and the relative humidity was approximately 36%. When the surface temperature of the composite insulator was not in excess of ±0.1 °C for 15 minutes, it was determined to reach equilibrium. For the insulator samples adopted in the experiment, the equilibrium time of each temperature measuring point was in the vicinity of 90 minutes.

The results of the IR temperature measurements were corrected by taking the temperature of the probe in a normal temperature environment as a standard.

B. RESULTS OF THE THERMAL EQUILIBRIUM EXPERIMENT

According to the experimental results, in the presence of a thermal defect in the insulator, the surface near the defect has a high temperature, and the temperature far from the defect is low (Fig. 9). The heating morphology is similar to the simulation results.

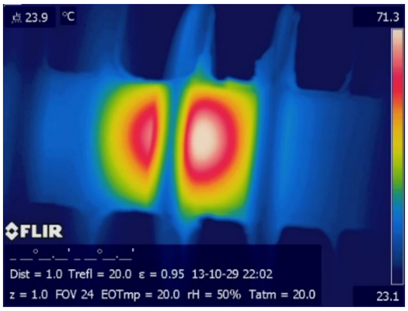


FIGURE 9. **Results of the thermal equilibrium experiment (without correction).**

With the enhanced heating power of internal defects, the external heating was more serious. Table 1 indicates the analysis results using different currents.

TABLE 1. Results of the thermal equilibrium experiment under laboratory conditions.

Current (A)	Defect temperature (℃)	Corrected IR results (℃)	Surface temperature rise (℃)
0	20.2	20.2	0
0.116	37.9	29.9	9.7
0.119	38.7	30.9	10.7
0.149	48.6	37	16.8
0.177	58.1	42.2	22
0.230	81.8	57.4	37.2
0.269	101.6	69	48.8

The results of the thermal equilibrium experiment further verify the linear relationship between the surface temperature rise and the defect temperature (Fig. 10). The laws summarized considering the theoretical analysis and simulation results are basically correct.

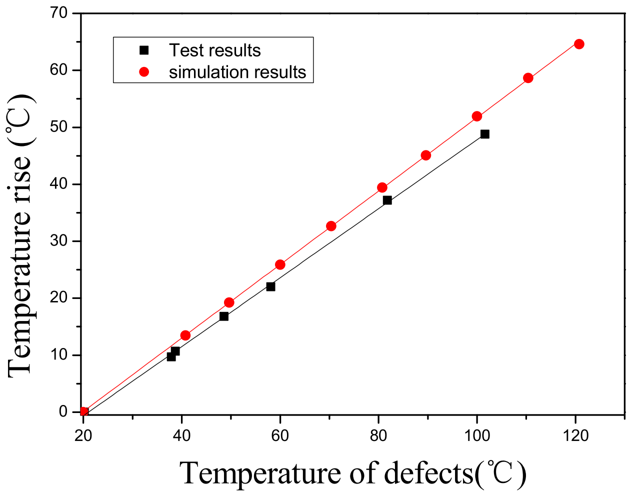


FIGURE 10. Simulation results and experimental results.

A comparison was drawn between the thermal equilibrium experimental results and the simulation analysis results for the same defect size. The experimental results are in good agreement with the simulation results (as exhibited in Fig. 10), which indicates:

(1) The surface heat transfer coefficient of the 500 kV insulator is approximately the same as that of the 220 kV insulator, which is 2.414. The umbrella structure has little impact on the heat transfer coefficient.

(2) The simulation results can be employed to study insulators with different sizes.

C. IMPACT EXERTED BY ENVIRONMENTAL FACTORS

The relative humidity and wind speed are deemed as two major factors in practical IR measurements of a composite insulator. In this regard, the relative humidity and wind speed were changed to examine in detail the IR detection results of composite insulators factoring in different wind speeds and humidity.

Given the on-site operating conditions, the impact exerted by the breeze condition on the IR measurement results was studied (as exhibited in Figs. 11, 12).

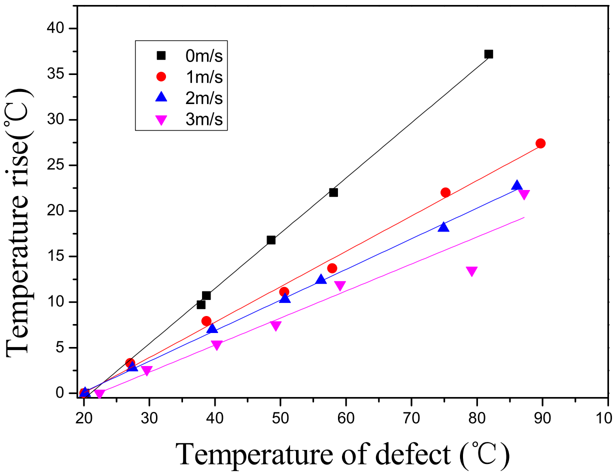


FIGURE 11. Influence of wind speed on IR temperature measurements.

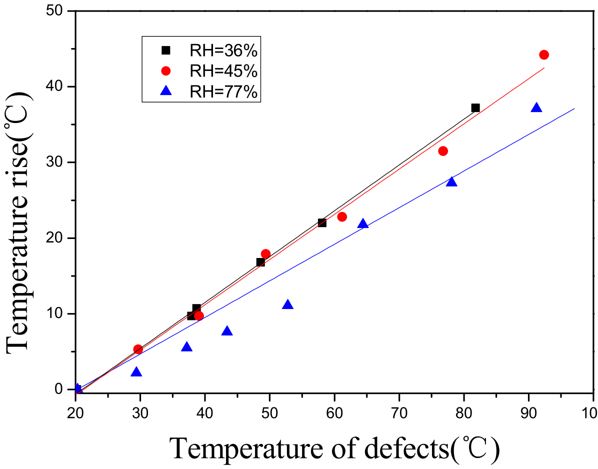


FIGURE 12. Influence of relative humidity on IR temperature measurements.

The experimental results indicate that the wind speed has a great impact on the temperature measurement results. When the internal defect was 80 °C, the temperature rise of the insulator under the windless condition was up to 37 °C. In contrast, under the condition of a 3 m/s breeze, the temperature rise of the insulator was only 15 °C. When the wind speed increased, the convective heat transfer process on the surface of the insulator was more severe, viz. β was smaller. As shown by Eq. 8, the temperature rise decreases when the defect temperature is constant, which is consistent with the experimental results.

Humidity had a similar effect on the IR temperature rise (as exhibited in Fig. 10). With an increase in humidity, β was smaller and the IR temperature rise decreased. However, the impact exerted by humidity was small in contrast to that exerted by the wind speed. When the defect temperature was 80 °C, the temperature rise under low humidity was approximately 37 °C. However, the temperature rise with high humidity was close to 28 °C.

The defect temperature and the external temperature rise of the composite insulator were proved to be linearly related to each other by the simplified model calculation, the simulation analysis, and the experiments under various natural environments. Given the boundary conditions, the relation between the surface temperature rise T_2 and the internal defect temperature T_1 is given in Eq. (9), where M denotes the umbrella structure of the insulator, E is the environmental factors, which are principally represented by the wind speed W and relative humidity RH, and D is the defect size.

$$T_2 = f(M, E(W, RH), D)(T_1 - T_0) \tag{9}$$

In accordance with the experimental results, since the k of the 220 kV and 500 kV insulators is the same, the main interest of study was 220 kV and 500kV insulators, thus M is negligible. The relationships between f and W and between RH and D are exhibited in Figs. 9, 10 and 4a.

Accordingly, the IR measurements of defects with different sizes, different wind speeds and relative humidity can be converted. If the IR detection results of a defect in a different period change markedly after eliminating the impact exerted by environmental factors such as wind speed and relative humidity, the internal defects of the insulator are asserted to be deteriorating rapidly based on adequate evidence despite the unchanged shape and size of the IR picture.

D. THE RELATIONSHIP BETWEEN AGING AND ABSORPTION

In section III.C, when studying the effect of heating, we used samples with less damage. But as a detection method, the purpose was to find defective insulator. Since the effect of humidity on heating was very complex, especially for the aged insulators, it still needed further studies.

In order to understand the effect of humidity on heating, we started to analyze the relationship between aging and water absorption. 4 samples with various running duration (3, 11, 14, 22 years) were selected. Then we cut out silicone rubber material with a uniformed thickness (2mm) from umbrella. Dehydrated for 24 hours in 60°C, until the weight remained stable and recorded as initial weight m_0. Then we put it in the incubator with constant temperature and constant humidity, the comparative humidity was 100%, temperature controlled to 20±3°C. Next, we periodically measured weight and documented as $m(t)$. So the absorption rate w(t) could be calculated as Eq.(10), which t represented the water absorption time. The entire experiment maintained for 239.5h.

$$w(t) = \frac{m(t) - m_0}{m_0} \times 100\% \tag{10}$$

The water molecules will enter the silicone rubber and fill in the free volume of the material firstly. And then, both the physical bonding and chemical bonding will occur between the water and material. The bonding coefficient α and dissociation coefficient β have been defined to describe the interaction between water and silicone rubber. For instance, in somewhere (z) of the material, if the amount of the free water molecules is n, and the amount of bonding ones is N, the generation rate of the bonding water which converted from free water was αn, while the dissociation rate from bonding water to free water was βN [19]. And we describe the absorption process of polymer material with the modified Langmuir diffusion method [20]:

$$\begin{aligned} D\frac{\partial^2 n}{\partial z^2} &= \frac{\partial n}{\partial t} + \frac{\partial N}{\partial t} \\ \frac{\partial N}{\partial t} &= \alpha n - \beta N \end{aligned} \tag{11}$$

The solution was as following:

$$\begin{aligned} \frac{w(t)}{w_s} &= \left[\begin{array}{l} \dfrac{\alpha}{\alpha+\beta}\exp(-\alpha t)(y(t) - 1) \\ \quad + \exp(-\beta t)(\dfrac{\beta}{\alpha+\beta} - 1) + 1 \end{array} \right] \\ y(t) &= 1 \\ &\quad - \frac{8}{\pi^2}\sum\nolimits_{j=0}^{\infty} \left\{ \begin{array}{l} \dfrac{1}{(2j+1)^2} \\ \exp(-(\dfrac{2j+1}{2})^2)\cdot\pi^2\cdot 4Dts^{-2} \end{array} \right\} \end{aligned} \tag{12}$$

w_s was the saturated absorption amount, t was absorption time, s was sample thickness, D was the water diffusion coefficient within the material.

To testify the accuracy of Eq.(12), according to the general solution of Eq.(12), we conducted fitting analysis for absorption results based on the particle swarm optimization algorithm using MATLAB software. The fitting results in Figure 13 was satisfying and proved that: the absorption process in the silicone rubber can be described with the Langmuir diffusion method.

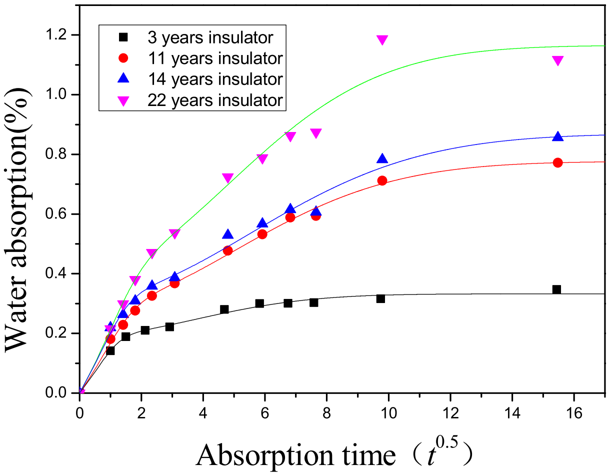


FIGURE 13. **The absorption results for insulators with different operating years.**

From Figure 13 we would know that as aging intensified, the rate of water absorption as well as saturated water absorption would increase. In order to analyze this phenomenon, we detects voids proportion of silicone rubber using mercury intrusion porosimetry (MIP). The results were listed in Table 2.

TABLE 2. **Results of MIP test for insulators.**

Operating years (a)	Porosity (%)
3	8.99
11	11.45
14	12.26
22	13.76

According to MIP test, there might exist more free volumes inside of aged silicone rubber material. Aging lead to breakup of chemical bounds [4], sabotaged the reticular structure within, resulting in leakage of partial fillers. After analyzing the mechanism of water absorption of silicone rubber, the increase in free volumes would certainly improve the water absorption properties of silicone rubber material.

E. THE RELATIONSHIP BETWEEN WATER ABSORPTION OF SILICONE RUBBER AND DIELECTRIC

When silicone rubber intruded by water, if we applied alternating electrical field, the polarization loss of water would lead to heating. The dielectric loss angle tan δ was an essential index for describing polarization loss of equipment, therefore we conducted tan δ tests on short insulation samples with different level of water absorption. In order to avoid the effect of superficial leakage current on test, all samples kept umbrellas. Samples had been in service for 14 years and the length 25mm. The diameter of round pad electrode was 80mm. The electrode and dielectric loss angle under various voltage were demonstrated in Figure 14.

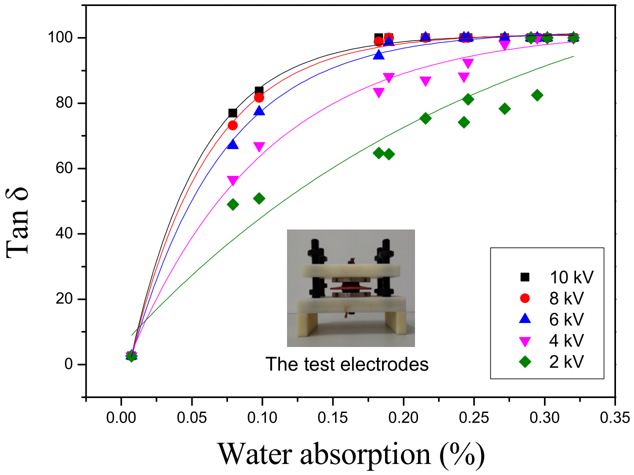


FIGURE 14. **The tan δ test results for insulators under different voltages with different water absorption.**

The absorption amount in Figure 14 was in fact the absorption amount of short samples of insulators, which was comprised of water absorption of silicone rubber material and internal core. Because the core was strictly sealed within silicone rubber and the absorption characteristics is different, the absorption amount was smaller than the silicone rubber exposed outside. Hence the absorption amount in Figure 14 was smaller than that of silicone rubber in Figure 13.

From Figure 14, we understood that for aged insulators, the tan δ would increase sharply with the intrusion of water. For polarization heating, the heating power density p conformed to Eq.(13). E referred to electrical field, while ε referred to dielectric constant:

$$p = \omega\varepsilon_0\varepsilon_r E^2 \tan\delta \tag{13}$$

Hence, when serious aging had happened to insulators surrounded by dense of water (high humidity), the water absorption of silicone rubber would increase (Figure.13), leading to more water intrusion into insulators and sharply increase of tan δ even up to 100%. The temperature of the insulators would rise even the high humidity was beneficial for heat dissipation, which explained various IR detection under different humidity when it comes to insulators with different level of aging. Meanwhile, was not only related water absorption amount according to Fig.14, it also was related to the intensity of electrical field. With greater electrical field, rotation of the water molecules could be more intense and the dielectric loss would increase, which lead to the increase of tan δ. And the heating was not only related to the tan δ but also proportional to the square of electrical intensity. Therefore, the heating would increase under high level of humidity and electric field. In fact, the result obtained in field that heating always occurred in the high voltage side of the insulator prove the conclusion.

The effect of water on insulator's heating contained 2 aspects: (1) to improve dissipation of heat and decrease the temperature rise which was proved in Fig. 12. (2) Intensify polarization to increase the temperature rise. Therefore, we should be more cautious while analyzing the heating reasons of composite insulators especially for ones operated in the area with high humidity. For new and slightly aged insulators, the temperature rise could be lower under high humidity. And the IR results can be revised with results shown in Fig. 12. On the contrary, the temperature might be higher under high humidity when serious aging has occurred to the insulators, the polarization was majorly responsible for the heating process.

IV. EXPERIMENTAL RESULTS

The results in this paper indicate that when tiny gaps remain in a composite insulator that result in a partial discharge and the defect temperature consequently thermally decomposes the silicone rubber, the external temperature rise can possibly remain under 1 °C. The external field intensity except for the high voltage end is comparatively low, and the water polarization has nearly no interference. Therefore, it is of critical significance to highlight the heating phenomenon in the low voltage area, and the detection of the composite insulator should rigorously abide by the standard.

An internal defect of a composite insulator poses a remarkable underlying danger to the performance of the insulator. This paper sought to detect the slight defects occurring with a partial discharge in a composite insulator through IR detection. However, power supply units are subject to numerous problems while adopting the IR detection method, which substantially reduces the effectiveness of the IR detection method. Although an acid resistant core has been used, there have been more than 10 similar fracture faults in recent years in China.

One of the underlying reasons for this phenomenon is that the measurement condition for IR detection is not explicit, and the qualifying method remains to be refined. The suggested passing standard in China's electricity industry is 0.5∼1 K. However, practical experience has proven that the standard is excessively rigorous, which results in frequent false alarms. In this regard, the passing threshold has been enhanced to different degrees. For instance, the operating instructions of China Southern Power Grid stipulates that the temperature rise shall not exceed 20 K [21].

However, in line with the simulation results, when the internal defects of the composite insulators are small air gaps (which is the most common form of internal defect), even if the temperature of the silicone rubber material near the defect increases up to 200 °C due to the fierce discharge in the insulator and the material property taken on by the silicone rubber has declined [22], the surface temperature rise remains under 1 °C. Therefore, blindly relaxing the existing standard is not conducive to the detection of small gap defects.

The authors have analysis in excess of 100 abnormally heated composite operated in high temperature and high humidity areas in South China (Fig 15), and they has been replace for they did not meet the existing standards. As the detection results indicate, 4 composite insulators heated over 5, and inner air gap has been found in all of them after dissection. 98 composite insulators heated 1-5°C under high humidity (RH>75%), but under low humidity (RH<35%), the temperature rise is less than 1 °C.and the electrical performance and mechanical performance of the 98 composite insulators still remain with a high level.

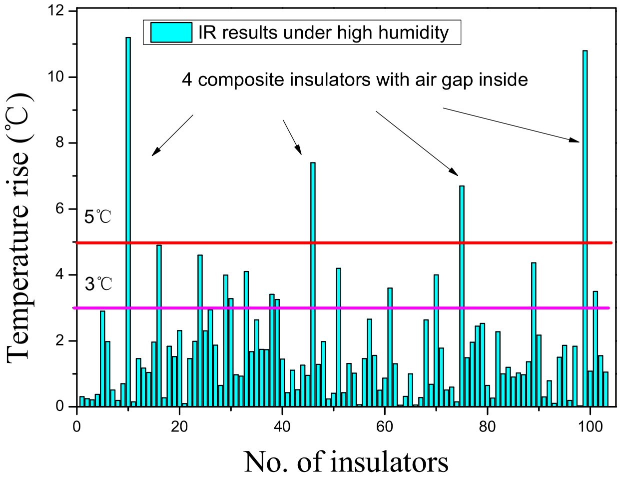


FIGURE 15. **IR results of insulators operated under high humidity.**

The main factors interfering with the on-site IR detection of the composite insulators include moisture polarization and contamination current. Moisture polarization plays a leading role in the alternating current composite insulator [23]. To reduce the false alarm rate, it is crucial to eliminate the interference of humidity and other environmental factors on the IR detection results.

Given the detection methods and criteria of composite insulators, especially in high humidity and under other unfavorable weather conditions, this paper proposes the following suggestions, which have been accepted by standard called "Classification standard of the transmission equipment operated in the China Southern Power Grid (Operation Brochure)":

(1) Composite insulators with a maximum temperature rise greater than 5 °C at the high voltage end should be renewed in time.

The heat dissipation process is intensified as the humidity increases (as exhibited in Fig. 10). Therefore, moisture polarization will not cause an extremely high surface temperature rise. The detection results of more than 100 insulators indicate that the temperature rise stemming from polarization alone does not exceed 5 °C.

(2) When the temperature is 3∼5 °C there might not be an inner defect existed inside and the replacement of the insulators is not urgent, but the products is still suggested to be replaced in the next maintenance round, for the accelerating aging process caused by heating and error of IR measurement caused by environmental factors (See fig.11,12).

(3) When the temperature rise is 1∼5 °C, the composite insulator should be redetected in a dry environment (RH < 40%). If the temperature rise remains above 1 °C, the composite insulator should be renewed.

After eliminating any water disturbance, if the temperature rise remains evident at the high voltage end, a marked air gap may be in the composite insulator.

(4) When the temperature rise in other areas except for the high voltage side surpasses 1 °C, the composite insulator should be renewed.

The results in this paper indicate that when tiny gaps remain in a composite insulator that result in a partial discharge and the defect temperature consequently thermally decomposes the silicone rubber, the external temperature rise can possibly remain under 1 °C. But the accurate quantitative relationship between the size of the defects and heating area was influenced by the types of the defects and was quite complex, which needs a further research. The external field intensity except for the high voltage end is comparatively low, and the water polarization has nearly no interference. Therefore, it is of critical significance to highlight the heating phenomenon in the low voltage area, and the detection of the composite insulator should rigorously abide by the standard.

V. CONCLUSIONS

1. Based on the numerical simulation, simulation modeling and experimental results, the temperature rise of defects in composite insulators and the external temperature rise are rigorously consistent with a linear relationship.

2. The slope of the straight line is predominately affected by the wind speed, relative humidity, and defect size and properties. The slope is negatively correlated with wind speed and relative humidity and is positively correlated with the defect size. The IR detection method is better for the recognition of conductivity defects of a carbonization channel and a large amount of water intrusion. However, in the presence of tiny air defects in the insulator, even if the temperature of the internal defect has exceeded 200 °C, the external temperature rise remains below 1 °C.

3. To optimize the existing detection standard for composite insulators, an AC composite insulator should be detected in a dry environment to the extent that this is possible. Nevertheless, after eliminating the interference of water, electric field and other related factors, the study should be conducted in accordance with the existing standards. It is inadvisable to blindly enhance the passing threshold for a temperature rise.

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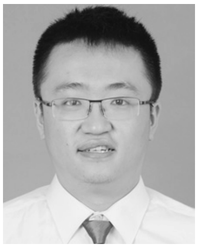

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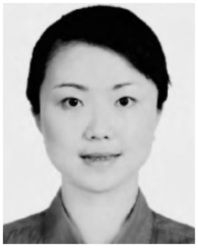

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