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Studying AC Flashover Performance of Suspension Insulators Under Natural Cold Fog and Wet Deposition Conditions

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ABSTRACT The electrical performance of insulators under comprehensive conditions including low air pressure, pollution and icing, is an important basis for the selection of external insulation. However, the problem of cold wet deposition has not attracted extensive and considerable interest in research. Based on flashover tests of suspension insulators in field test station, the AC flashover performance of insulators was studied. The results show that the duration of existence of the arc throughout the composite insulator surface in case of condensation was significantly lower than that in case of freezing fog flashover because of a change of the sheds surface roughness, which leads the arc melt the frozen fog droplets on the sheds surface and extends its flashover time. Compared with the flashover characteristics of the hydrophilic insulators in frost fog, the composite insulators exhibited clear arc extinguishing and arc starting phenomena. Moreover, the wind velocity has affected the flashover performance of suspension insulators in cold fog. Studying flashover characteristics of suspension insulators can contribute to the design of the external insulation of transmission lines and substations under natural cold fog and wet deposition regions.

INDEX TERMS Test station, natural fog, cold wet deposition, insulator, ac flashover performance.

I. INTRODUCTION

The electrical characteristics of insulators of transmission lines play a decisive role in the safety of power systems [1]. In the normal environment, the electrical performance of insulators meets the requirements of line operation. China is a vast country with a large span of transmission lines in the east–west and north–south directions. With the continuous advancement of power grid construction, power grids have become increasingly denser and more widely distributed [2]. The power lines corridor inevitably passes through areas with cold fog and wet deposition areas, where the ice and snow significantly reduce the electrical strength of the insulator [3], [4]. The problem of the icing and snowing of transmission lines is one where the electric field distribution of the umbrella skirt is distorted due to the bridging of the surface of the insulator, which is caused by supercooled water droplets falling on the surface of the insulator [5]. Flashover thus occurs along the surface of insulator at the operating voltage, which can cause large blackouts or even a fire.

Because many regions of South China receive a large amount of rain and snow every year, the problem of cold wet deposition has attracted considerable interest in research [5], [6]. Systematic research has been carried out on the icing of and snow cover on insulators that has revealed important characteristics related to flashover and discharge development, which will help prevent and mitigate these problems in power grids [7]–[9]. Studies in this field have considered the physical characteristics of the icing surface, test methods, characteristics or mathematical models of iced insulators to determine the various factors and mechanism of flashover due to icing. The influence on the insulator of the type of icing, salt density of pollution, conductivity of the icing water, amount of icing, air pressure, and the

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type of voltage applied have thus been determined [10]–[14]. Prevalent research has been mainly based on the electrical characteristics of insulators under artificial climatic conditions, which are different from conditions of the operating environment [15]–[17]. Due to the freezing of supercooled droplets on the surface of the insulator, the problems of icing and snow on it arise in cold and foggy environments. Conducting experiments on flashovers in cold fog to study the characteristics of the insulator in such conditions is thus important. No specialized method for this is available in China, whereas long-term studies have been carried out across the world on the flashover characteristics of the insulator in cold and foggy conditions by using artificial climate chambers [5], [14], [18], [19]. Cold fog flashover is common in China, but it has been classified as pollution flashover even though its process of development and characteristics are significantly different [20]. Few studies with this particular aim have been conducted, and the relationship between the process of development of the flashover whose arc along insulator surface and environmental factors lacks supports of from field tests [21]–[23].

In light of the above, this paper examines cold fog flashover of suspension insulators in an environment featuring cold and wet deposition. A field test was carried out in the Field Scientific Observation and Research Station of the Ministry of Energy Equipment Safety in Xuefeng Mountain to study the characteristics of strings of a suspension insulator in case of AC cold fog flashover. From the end of December 2019 to February of the following year, natural fog droplets were used to freeze the surface of the insulator and voltage was applied until the arc flashover had formed. Knowledge of the characteristics of the insulator in these conditions can also contribute to the design of the external insulation of transmission lines in areas with cold fog and wet deposition.

II. TEST EQUIPMENT, SPECIMENS AND PROCEDURE

A. EXPERIMENTAL EQUIPMENT

The field tests were conducted in Xuefeng Mountain testing station. Fig. 1 shows a circuit schematic diagram in which the source components are a TDJY-1000kVA/10kV voltage regulator (T), a YDJ-200kVA/100kV test transformer (B) and a 15kΩ protective resistor (R_0). The technical parameters of the voltage supply comply with the requirement introduced by the relevant testing standards [24], [25]. The AC power is led to the test objects (S) through a wall bushing (H). The testing voltage is measured by an AC capacitive voltage divider with a ratio of 10 000:1 (the ratio of capacitance at the high capacitor C_1-150pF to capacitance at the low terminal C_2-1.50μF).

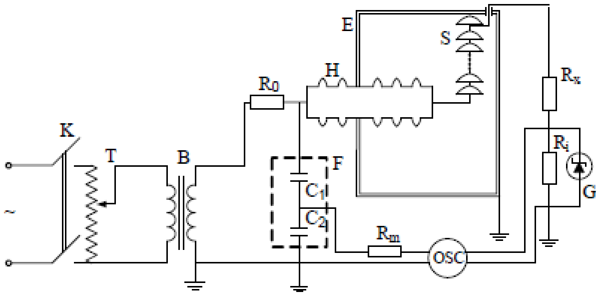


FIGURE 1. Test circuit diagram of specimen experiment.

B. SPECIMENS

Two silicone rubber composite insulators, FXBW-10/70 (Type A-B), and two three-disk ceramic insulators—LXY-70 (Type C) and XP-70 (Type D), which are widely applied in power grids in China, were used as specimens. The main dimensions and profiles of the suspension insulators are presented in Table 1, where H represents its geometric height, *h* is the spacing between unit, *D* and *d* are the diameters of the large and small sheds, respectively, *L* is the leakage distance, and *A* is the surface area.

TABLE 1. Parameters and configuration of insulator.

Type	*H* /mm	*h*/m	*D*-d /mm	*L* /mm	*A* /cm^2
A	415	225	130/100	600	3569
B	356	182	158/128	500	2834
C	146	/	255	600	1733
D	146	/	255	600	1733

C. TEST PROCEDURE

1) PREPARING THE SPECIMEN

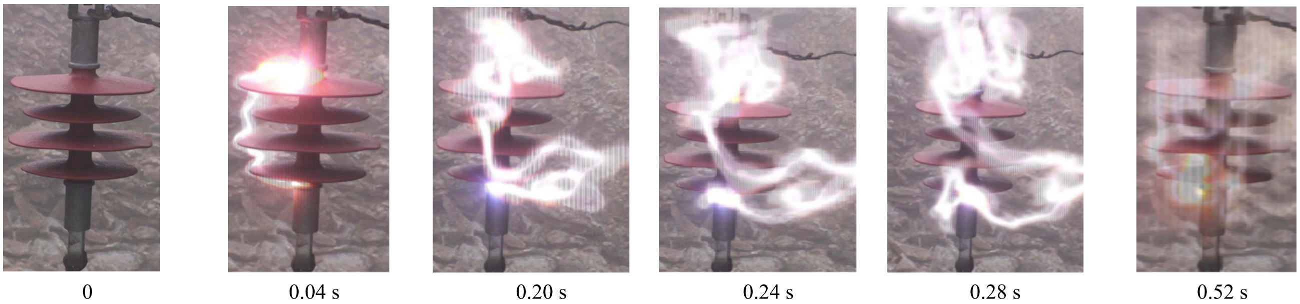
Because of adverse natural conditions of the environment considered here, the tests could not be rendered completely conformant with the standard [24], [25]. The surfaces of the insulators, including the steel cap and pin, were cleaned with tap water and trisodium phosphate (Na_3PO_3) to remove all traces of dirt and grease, and then allowed to dry [3]. Tap water ($\gamma_{20} < 30\mu$S/cm) near the station was used.

2) TEST PROCEDURE

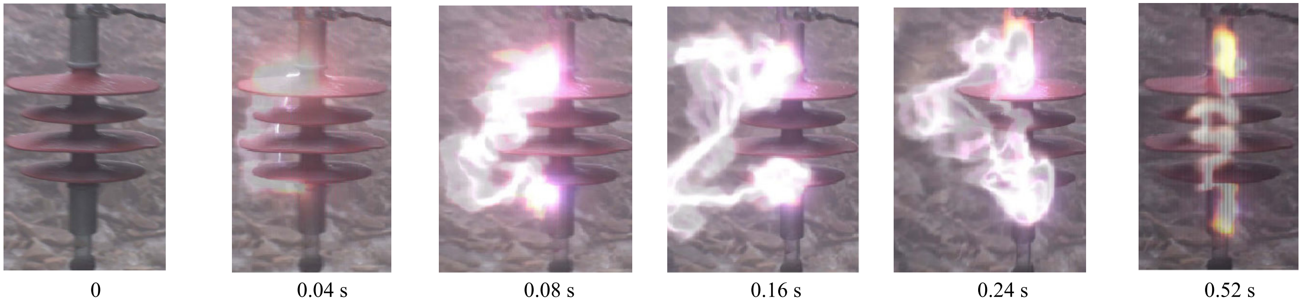
a: COLD FOG WETTING

The surfaces of the insulators were wetted by natural cold fog over three weeks. In the worst case, the visibility in fog was less than 50 m and the relative humidity was 99.8%. The climatic conditions satisfied the wetting requirements of the insulator surface. The insulators were suspended on a test shelf outdoor in the presence of heavy fog. The surfaces of the specimens were thus wetted completely over about 2h, as shown in Fig. 2.

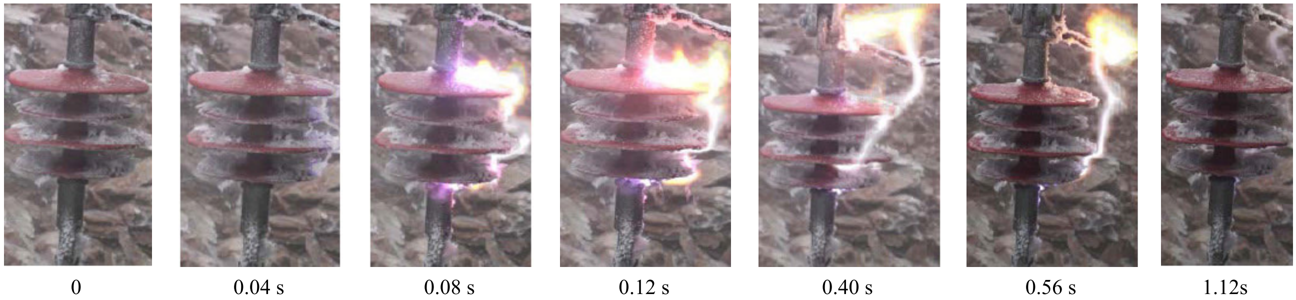
FIGURE 2. Surface of an insulator wetted by natural fog.



(a) Condensation fog flashover in the evening on December 25



(b) Dense fog flashover on the morning of December 26



(c) Cold fog flashover on the night of December 26

FIGURE 3. **Flashover processes of composite insulator from December 25 to 26, 2019.**

Measuring method of environmental parameters: A laser scattering particle analyzer was used to measure the water content and diameter of the fog droplets over a test range of 4.6μm–323μm. The error was smaller than 3%, and the length of the measurement area was 1–10m. The wind velocity was measured by an AVM-03 vane wheel anemometer with a range of 0.3–40.0m/s and a resolution of 0.1m/s. The range of measurement of the temperature sensor was -40°C to $+80$°C, and the error in its measurements was ±0.3°C. The range of measurements of the capacitive relative humidity sensor was 0%–100% and its errors were ±2% (when relative humidity was less than 80%), and ±5% ($\geq$80%). The AC flashover test of the insulator involved repeatedly applying voltage during the condensation of fog in the naturally cold and wet deposition environment [3]. The ambient temperature was -5°C–5°C, and the frozen surface of the insulator complied with the test requirements under natural cold fog conditions.

b: APPLIED VOLTAGE METHOD

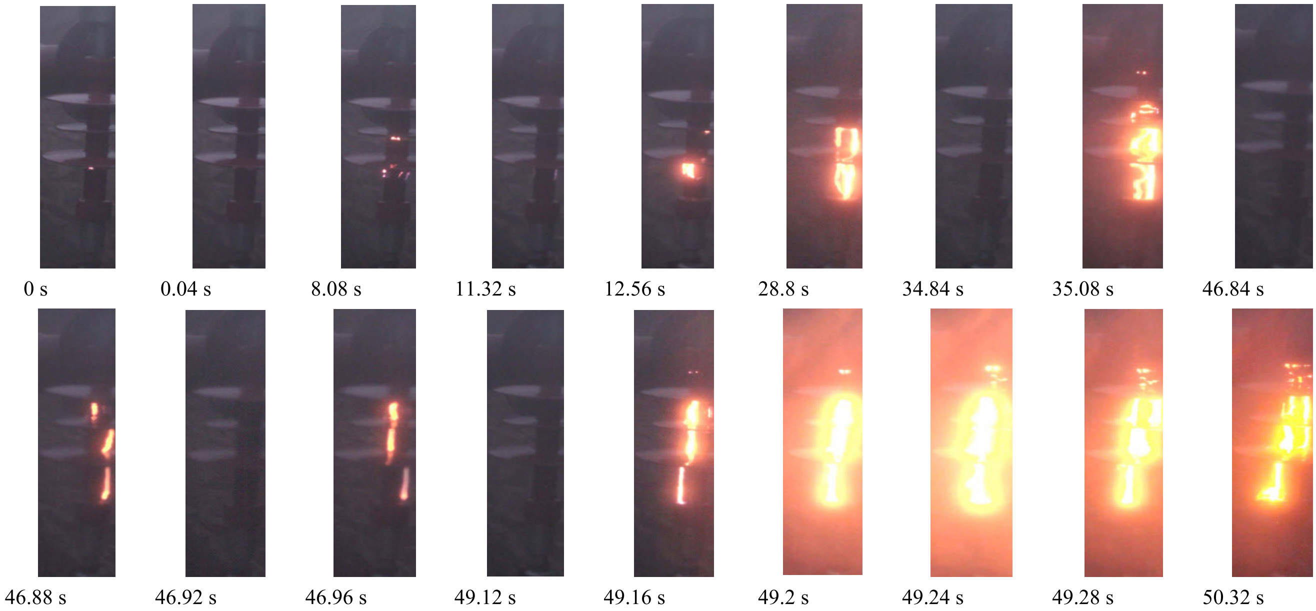
The even-rising voltage method was applied until the full flashover, and the flashover process was captured by a high-speed Sony frame camera [3], [5]. However, the wind velocity and humidity constantly changed during the field tests. Therefore, the ambient temperature, humidity and the wind velocity were recorded during each test. The variable weather conditions of outdoor test sites can lead to differences in atmospheric conditions. To obtain valid test data, the variation in ambient temperature was kept to within 2°C for each test, and the average value of measurements was regarded as the temperature [3].

III. TEST RESULTS AND ANALYSES

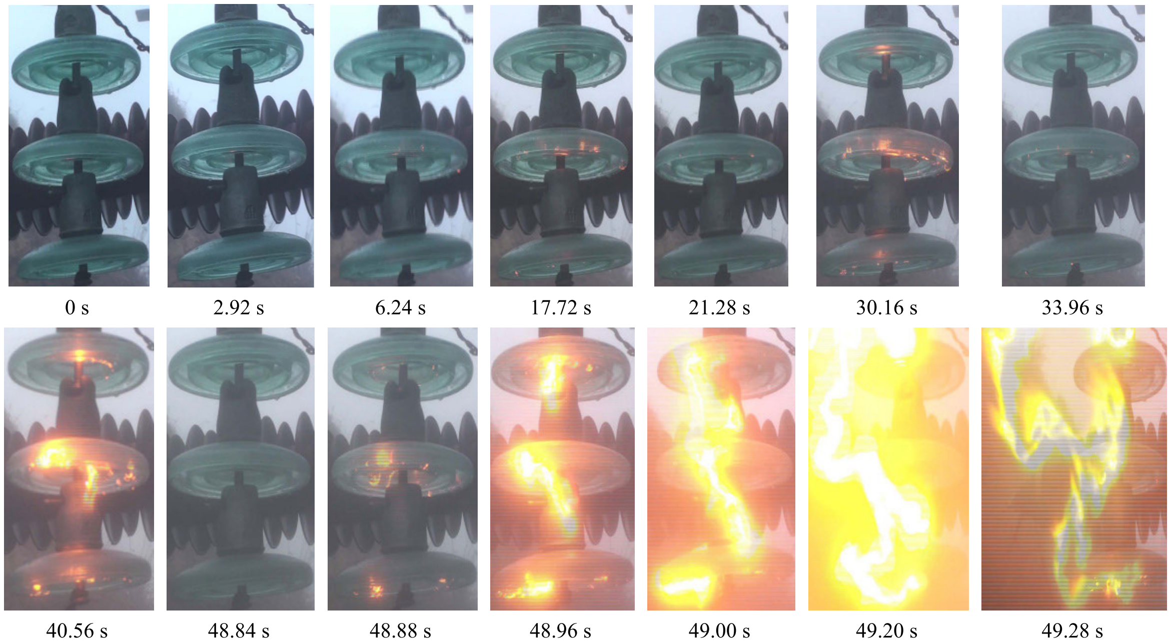
A. FLASHOVER CHARACTERISTICS OF COMPOSITE INSULATOR UNDER NATURAL FOG ENVIRONMENT

From December 25 to 26, 2019, AC flashover tests were carried out on the composite insulator in the field test station under condensation fog, dense fog, and freezing fog, respectively. The flashover discharge process was captured by the high-speed Sony frame camera as shown in Fig. 3.

It can be seen from Fig.3 that the arc process of the composite insulator in the case of condensation and dense fog is significantly different from in the freezing fog environment. In Fig. 3(a), the arc is bright-colored when it passes through both ends of the insulator shed for the first time, and the



(a) Composite insulator



(b) Glass insulator

FIGURE 4. **Cold fog flashover in insulators from November 2018 to February 2020.**

time taken for the development of the full flashover's arc was 0.48s—identical to that needed in dense fog but significantly shorter than that shown in Fig. 3(c), in a cold fog environment (1.08s). The shed of the composite insulator was made of silicone rubber, which is strongly hydrophobic, in the cold fog environment. When the supercooled fog droplets collided with the shed surface of the insulator, they condensed into a layer of thin ice/snow due to the difference in heat capacity, and the surface roughness of the insulator shed changed. Under the operation of the AC power supply, part of the energy was absorbed by the melting of the frozen fog droplets during arc combustion such that the time needed for the flashover of the arc was prolonged. In addition, the discharge arc represented irregularly shaped bends, and exhibited a red burning flame or swayed violently.

B. CHARACTERISTICS OF INSULATOR IN CASE OF COLD FOG FLASHOVER

From November 2019 to February 2020, the authors carried out a large number of cold fog flashover tests on a composite insulator and a glass string insulator in the field test station. The process of arc development along the surface of the insulator shed is shown in Fig. 4. Fig. 4 shows the following:

(1) The duration of arc bridging at both ends of three glass insulator strings in the cold fog environment was 0.28 s (49s–49.28s) and the color of the arc of the flashover was yellowish-white. The penetrability arc developed quickly, and the duration of arc occurrence and development before surface flashover was 49s.

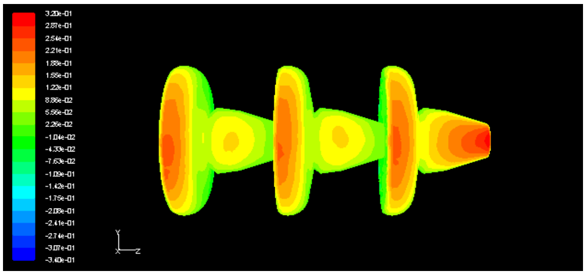
(2) The process of flashover of the composite insulator featured a clear stage of the occurrence and development of the arc in cold fo. Also, the prominent extinguishing and starting phenomena of the arc were observed. The duration of arc bridging at both ends of the composite insulator was 1.12s–1.28s, and the arc was flame red. The penetrability arc was disordered and scattered in the dense fog around the insulator shed. It is different from the development of the arc flashover of the hydrophilic glass insulator, the duration of arc development along the surface of the composite insulator was 50.32s; in contrast to the concentration of the arc during flashover of the polluted insulator, the penetrability arc developed quickly, and there was no clear arc before flashover.

C. INFLUENCE OF WIND SPEED ON SURFACE ARC OF INSULATOR IN COLD FOG

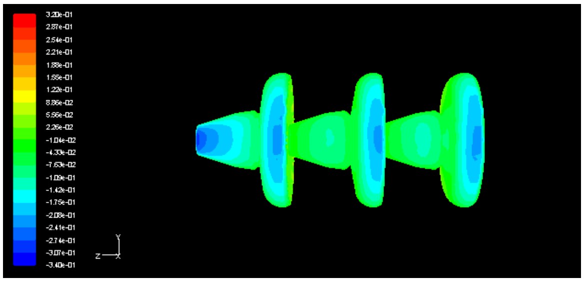
1) ANALYSIS OF AIR FLOW FIELD AROUND INSULATOR STRINGS

Air flow around the insulator was turbulent, and the transient motion of the turbulence was described using the unsteady Navier–Stokes equation. To study the characteristics of flashover of the insulator strings at different wind speeds, the Navier–Stokes equation and the finite element simulation were used to calculate the distributions of velocity and static pressure of air flow around the insulator strings based on the FLUENT fluid dynamics simulation software. Fig. 5 shows the static pressure of the XP-70 porcelain insulator at wind speeds of 0.1m/s and 7m/s (unit: Pa), where the pressure on the windward side was on the left and that on the leeward side was on the right.

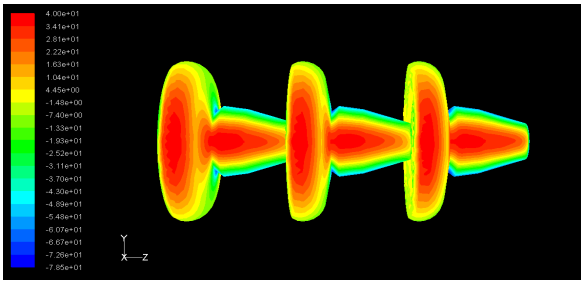
According to Fig. 5, when the wind speed was 0.1m/s, the static pressure on the surface of the windward side of the insulator was small, and the order of magnitude of the maximum static pressure was only 10^{-1}; In addition to this, the static pressure on the leeward side was even smaller, approximately zero or negative. When the wind speed increased to 7m/s, the static pressure on the windward side of the insulator was much higher than that on the leeward side.



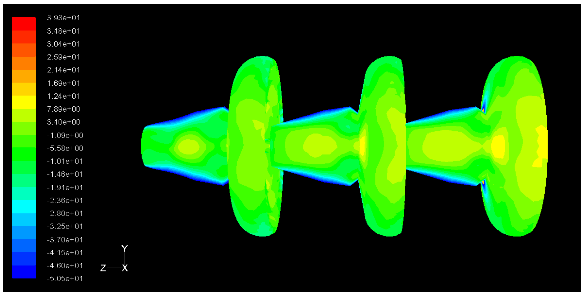
windward side



leeward side
(a) *v*=0.1 m/s



windward side

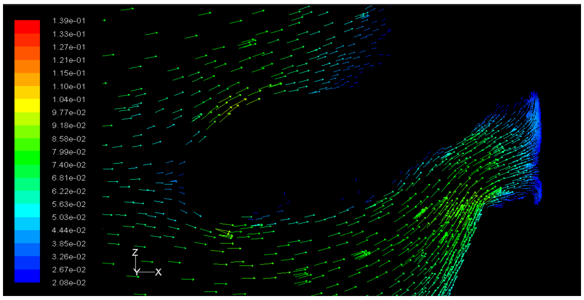


leeward side
(b) *v*=7 m/s

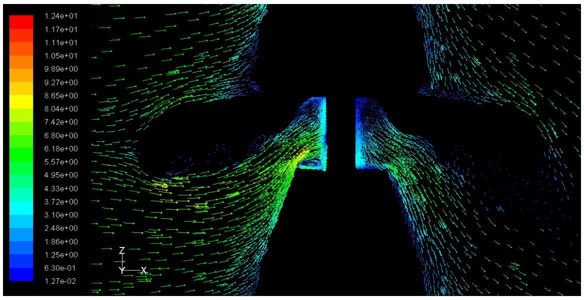
FIGURE 5. **Static pressure on the insulator surface at v = 0.1 and 7 m/s.**

Fig. 6 shows a diagram of the distributions of different velocity flow fields of the XP-70 insulator on the $y = 0$ section. When the wind speed was low (weak wind condition), air flow around the insulator was relatively simple and weak. The edge along the lower surface of the insulator's shed caused an eddy current. Fig. 7 shows the cross-section of its lower surface at $z = 0.192$mm at a wind speed of 7m/s. Compared with the weak wind environment, turbulent diffusion along the edge of the insulator was more prominent in a strong wind environment.

Therefore, when the wind speed was low, the drag force of the local arc was approximately the same order of magnitude as its electrostatic force and thermal buoyancy. The drag force and electrostatic force of the fluid were counteracted in part, and the effect of thermal buoyancy on the local arc was more prominent. The local arc on the lower surface of the shed was close to the groove, but it on the upper surface floated away under the effect of thermal buoyancy to form an air gap arc, which was consistent with the arc



(a) v=0.1 m/s



(b) v=7 m/s

FIGURE 6. **Diagrams of the velocity vector near the insulator surface at v = 0.1 m/s and 7 m/s.**

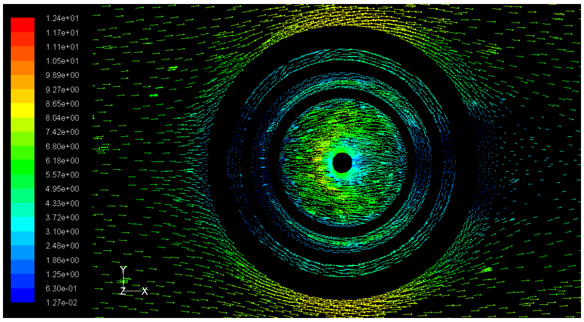


FIGURE 7. **Diagram of the velocity vector of the insulator with z = 0.192 mm at v = 7 m/s.**

floating phenomenon observed. During the test, the local arc developed along the lower surface of the insulator where the floating arc appeared. As wind speed increased, static pressure on the surface of the insulator was much higher than in the weak wind environment. That is to say, compared with fluid traction, the static power and thermal buoyancy of the arc were negligibly small. Fluid drag (i.e., air flow) plays an arc blowing role in the development of the arc, and the arc channel exhibits characteristics of non-surface discharge.

2) MECHANISM ANALYSIS OF AIR FLOW ON FLASHOVER CHARACTERISTICS

The experimental results show that air flow affected the flashover characteristics of the insulator mainly in the arc-building stage, the stage of formation of the main channel, and the dissipation stage, particularly the latter.

a: ARC-BUILDING STAGE

When the wind velocity was low or zero ($v < 2$m/s), the surface arc of the insulator mainly consisted of brush discharge, exhibiting a prominent arc bridging phenomenon, and gradually developed upward along the outer edge of the insulator shed. The discharge particle beam was bridged in an unstable state, and then conducted to form a linear arc column. With an increase in wind velocity ($v > 5$m/s), the umbrella group of the insulator was bridged by the discharge particle bundle, and the arc column branched and developed upward. When the wind velocity further increased ($v > 10$m/s), the phenomenon of the bridging of the two ends of the insulator by the discharge particle bundle was not observed, and arc flashover occurred immediately.

b: ARC FORMATION STAGE

When there was no wind, the path of the arc was short, clear and bright. When the wind velocity was low ($v < 2$m/s), the path was thicker, the boundary was fuzzy, and the arc post remained linear; when the wind velocity was high ($v > 5$m/s), many branches of the path of the arc formed, and both it and the channel of the discharge particle beam were close to the insulator outer edge.

c: ARC DISSIPATION STAGE

When there was no wind, the column of the arc thickened, became blurred, and then disappeared; when the wind velocity was low ($v < 2$m/s), the column stretched, twisted, thickened and blurred. It was then blown away by the wind; when the wind velocity was high ($v > 5$m/s), the branch of the arc stretched, the column of the arc of each branch became thick and blurry, and then dissipated. When the wind velocity was even higher ($v > 10$m/s), the tensile effect of the column was not prominent, and disappeared quickly.

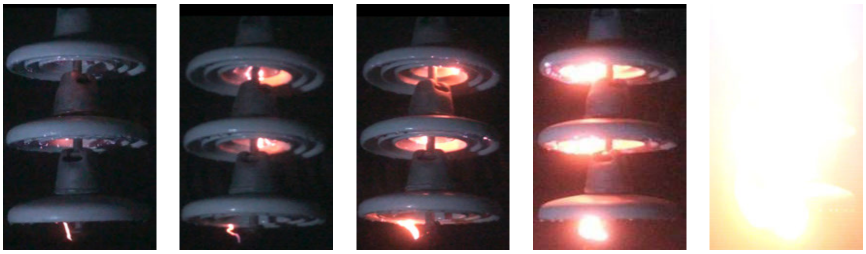
3) INFLUENCE OF WIND VELOCITY ON FLASHOVER CHARACTERISTICS

To investigate the influence of wind velocity on flashover characteristics, the authors captured the AC flashover process of the three units of insulators using a high-definition camera, as shown in Fig. 8 [3]. The atmospheric parameters were measured using the PTU-200 (−2–4°C, 95%–98%, 0–12m/s). The following can be observed:

(1) When v_a was low (0–2m/s, see Fig. 8(a)), some of the partial arcs deviated from the insulator surface and gradually formed an air gap arc with increasing applied voltage. The final discharge channel was a bright arc that directly ran through the shortest air gap distance between the high-voltage and low-voltage terminals. Moreover, the air gap arc exhibited the arc-levitating phenomenon before flashover.

(2) The effect of wind velocity on shapes of the discharge arc increased as v_a increasing (see Fig. 8(b)). The longer partial arc appears significant the extinction and reignition phenomena. The partial arcs showed a punctate distribution in a few cycles before the pre-flashover. Finally, the flashover arc presents multi-channel, messy and arc-levitating phenomena.

(3) The effect of wind velocity on shapes of the discharge arcs clearly changed as v_a further increased ($v_a = 6 - 12$ m/s,



(a) 0–2 m/s

(b) 2–5 m/s

(c) 6–12 m/s

FIGURE 8. **Flashover of insulator vs. various wind speeds.**

see Fig. 8(c)). The partial arcs are easily extinct and difficultly reignite. When the applied voltage had risen to a certain level, the partial arcs increased in length and brought about the arc-levitating phenomenon until complete flashover. The flashover arc always appeared downwind of the insulator strings, far from its surface, and exhibited the phenomenon of scattered non-creeping discharge.

IV. CONCLUSION

(1) During the AC flashover process of the condensation of the insulator owing to dense and freezing fog, the brightness of the partial arc was clearly different from the thickness of its root. The duration of existence of the arc throughout the composite insulator surface in case of condensation was significantly lower than that in case of freezing fog flashover because of appeared of arc-levitating from the insulators surface until changed of the surface roughness, which leads the arc melt the frozen fog droplets on the shed surface and extends its flashover time. Moreover, the discharge arc presents very irregular shapes bends, and has red burning flame or violently sway characteristics.

(2) Compared with the flashover characteristics of the hydrophilic insulator in frost fog, the composite insulator exhibited clear arc extinguishing and arc starting phenomena, and the duration of the arc at both ends of the bridge umbrella skirt was up to 1.12s–1.28s. The flashover occurred due to the connection between the surface arcs and the air gap of the adjacent insulator strings.

(3) The wind velocity influences the burning, elongation, extinction, and reignition of the partial arc, and finally flashover. The shapes of the discharge arcs became different with increasing wind velocity. The partial arcs show a multi-channel scattered distribution and appear arc-levitating phenomena from insulator surface in a few cycles before pre-flashover with increase of wind velocity.

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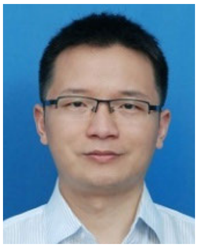

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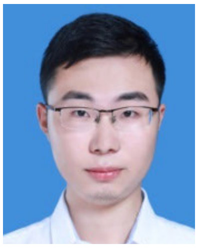

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