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Study on the Influence of the Inclination Angle of the Insulator on the Deformation and Flashover Behaviour of Water Droplet under AC Field

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ABSTRACT: The separation of water droplets on the insulator umbrella surface is an important factor that increases the probability of flashover along the surface. Previous studies have only investigated the motion and deformation of water droplets on the horizontal insulator sample surface and their effect on flashover voltage. In actual composite insulators, the umbrella skirt surface is usually inclined at a certain angle. The influence of the umbrella angle on the motion law and flashover voltage of water droplets has not been fully studied in recent research. In this paper, focusing on the separated water droplet on insulator sample surfaces with different inclination angles, the motion modes and flashover characteristics of the water droplet are studied by using multi-physics finite element simulation and AC flashover experiment. The results show that the motion modes of water droplets change with the inclination angle of the umbrella surface. The water droplet oscillates left and right under the AC electric field when the inclination angle is small. As the inclination angle increases, the oscillating trend of the water droplet weakens. When the inclination angle is large enough, the deformation of the water droplet shows two forms: sliding and stretching. As the inclination angle of the umbrella surface increases, the flashover voltage decreases, and the decreasing trend of the flashover voltage is greater when the inclination angle is larger.

1. INTRODUCTION

The small inclination angle umbrella-skirt composite insulators have been widely used in power grid construction due to its excellent characteristics, such as hydrophobicity and good self-cleaning properties [1, 2]. In high-humidity environments, however, some rain or mist may still adhere to the umbrella skirt surface in the form of separated water droplets, which are not easily slid off. When being exposed to an electric field, the water droplets become stretched and distorted to some degree, which alters the electric field distribution in their vicinity. The distortion of the electric field distribution increases the risk of flashover along the insulator surface [3]. Additionally, the distortion of the electric field distribution around the water droplets can cause localized corona discharge when severe, leading to accelerated aging of the skirt and compromising the hydrophobicity of the insulator surface [4].

Experimental studies on the deformation patterns of water droplets on the surface of flat insulators have been conducted by some researchers [5–8]. Studies have shown that water droplets exhibit various motion patterns under electric fields, and these patterns differ to some extent between AC and DC electric fields. Specifically, the movement of water exhibits certain regularity under AC electric fields [9–12]. However, there have been relatively few recent studies on the motion patterns of water droplets under different umbrella-skirt inclination angles. The changes in the umbrella-skirt inclination angle have certain impacts on the motion and surface flashover behavior of water droplets.

Therefore, in this paper, a multi-physics simulation software was used to simulate the motion behaviors of water droplets on the sample surface in an electric field-fluid field coupling manner. Additionally, an AC flashover experimental platform was set up to experimentally study the motion modes and flashover process of water droplets under different umbrella-skirt inclination angles.

2. MODELING AND SIMULATION COMPUTING

2.1. Models of Multi-Field Coupling

The motion patterns of water droplets under the influence of an electric field can be simulated by the Electrostatics-Fluid Flow module. To establish a dynamic model for water droplets, it is necessary to formulate the Navier-Stokes equations that describe fluid motion and accurately track and capture the fluid interfaces. The software offers an automatic formulation of the Navier-Stokes equations for fluid motion and the "Laminar Two-Phase Flow, Phase Field" interface, which enables the use of the phase field method to track fluid interfaces. This study utilizes the functionality provided by this interface to conduct a multiphysics coupling investigation of water droplet motion.

When coupling the electric field and fluid field, the electric field force acts on the water droplet through the fluid control equation, which is the Navier-Stokes equation. The governing

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equation is as follows:

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right] = \nabla\cdot(-p\mathbf{I})+\nabla\cdot\left[\mu(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)\right] + \rho g+\mathbf{F} \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0 \tag{2}$$

where $\mathbf{u}$, p, and ρ are the fluid velocities, pressure, and mass density, respectively. μ is the fluid kinematic viscosity, and ρg represents the gravity. Scalar p represents the pressure, and vector $\mathbf{I}$ represent the unit tensor. Thus $(-p\mathbf{I})$ is the normal stress tensor, and $\mu(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)$ is the shear stress tensor. The external force, denoted as $\mathbf{F}$ (primarily electric field force in this context), is determined by the divergence of the Maxwell stress tensor:

$$\mathbf{F}=\nabla\cdot\mathbf{T} \tag{3}$$

The Maxwell stress tensor is given by:

$$\mathbf{T}=\mathbf{E}\mathbf{D}^T-\frac{1}{2}(\mathbf{E}\cdot\mathbf{D})\mathbf{I} \tag{4}$$

where $\mathbf{E}$ is the electric field, and $\mathbf{D}$ is the electric displacement field:

$$\mathbf{E} = -\Delta V \tag{5}$$

$$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} \tag{6}$$

In the 2D model, the expression of the stress tensor is:

$$\mathbf{T} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \tag{7}$$

$$T_{xx} = \varepsilon_0\varepsilon_r E_x^2-\frac{1}{2}\varepsilon_0\varepsilon_r\left(E_x^2+E_y^2\right) \tag{8}$$

$$T_{xy} = \varepsilon_0\varepsilon_r E_x E_y \tag{9}$$

$$T_{yx} = \varepsilon_0\varepsilon_r E_y E_x \tag{10}$$

$$T_{yy} = \varepsilon_0\varepsilon_r E_y^2-\frac{1}{2}\varepsilon_0\varepsilon_r\left(E_x^2+E_y^2\right) \tag{11}$$

where ε_0 and ε_r represent the relative permittivity of oil and water, respectively. The electrostatic interface is used to calculate the composition of the electric field, and variables are defined to establish the expressions for calculating the stress tensor components. For the dynamic behavior of an inclined water droplet, the laminar flow interface needs to consider the effect of gravity.

2.2. The Results of Two-Dimensional under AC

The air computational domain of the two-phase simulation model in a two-dimensional water-air system is set as a rectangular shape with dimensions of 40 mm × 20 mm. For grid division, a free triangular meshing method is employed throughout the entire domain. The left electrode is grounded, and the simulation is initialized by applying a potential to the right electrode. The volume of the water droplet is set to 150 µL. The material properties used in the simulation model are listed in Table 1.

TABLE 1. Material properties for simulation.

Material Properties	Water	Air
Density (kg/m^3)	1000	1.29
Dynamic viscosity (Pa·s)	10^{-3}	17.9×10^{-6}
Relative permittivity	80	1

Under an AC electric field, as the electric field strength increases, the water droplets start to move due to the action of electric stress. At different umbrella surface inclinations, water droplets are influenced by the combined effects of electric field force, gravity, and surface tension between the water droplet and the sample. The motion of water droplets exhibits certain differences. In the simulations conducted in this study, a voltage of 5 kV/cm was applied to the electrodes at both ends.

When the inclination angle of the inclined plane is small (less than 10°), and the electric field strength increases, the water droplet oscillates and deviates in the opposite direction of the electric field, as shown in Figs. 1(a) and (b). In this case, a 50 Hz power frequency AC is applied, and each image is captured at intervals of 0.01 s. It can be seen that under the AC electric field when the inclination angle of the inclined surface is small, the water droplet does not move in the same direction, but oscillates and slightly elongates in the direction opposite to the intensity of the electric field.

With the increase of inclination angle of the inclined surface, when the inclination angle increases to 10°, the initial shape of the water droplet changes under their gravity, and the contact angle is no longer symmetrical. As the externally applied AC voltage continues to increase, the motion mode of the water droplet differs significantly from that at a small inclination angle, as shown in Fig. 1(c). The tendency of the water droplet to oscillate left and right is very weak. Its main form of motion is to elongate downwards along the inclined surface. When the direction of the electric field changes, the elongation length of the water droplet shrinks slightly. When the direction of the electric field changes again, the water droplet continues to elongate downwards along the inclined surface.

With a further increase in the inclination angle of the inclined surface, reaching 15° and above, the movement pattern of the water droplet becomes similar to that at a 10° inclination angle. However, the distinction is that at an inclination angle of 15° and above, the elongation of the water droplet is accompanied by a certain degree of sliding, as shown in Figs. 1(d), (e).

Based on the simulation of the dynamic behavior of water droplets under different inclined plane inclinations, the following conclusions can be drawn: Under AC electric fields, water droplets oscillate from left to right in the opposite direction of the electric field, and the oscillation frequency is consistent with the frequency of the electric field. With the increase in the inclination angle of the inclined surface, the oscillation of the water droplets weakens, and the motion of the water droplets is mainly elongating downwards along the inclined surface. When the inclination angle of the inclined surface is large enough, the water droplets will slip along the sample surface to some extent while stretching. When the inclination angle of the inclined surface reaches a certain angle, the water droplets will slip along the sample surface to some extent while stretching.

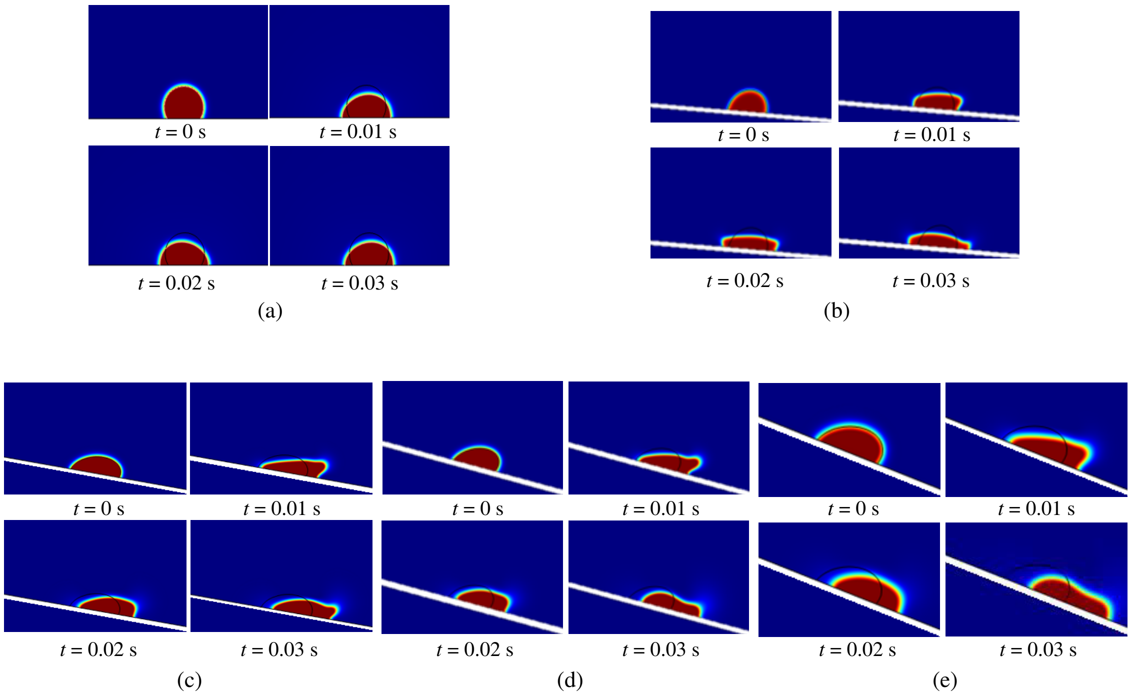


FIGURE 1. The results of simulation under different inclination angle.

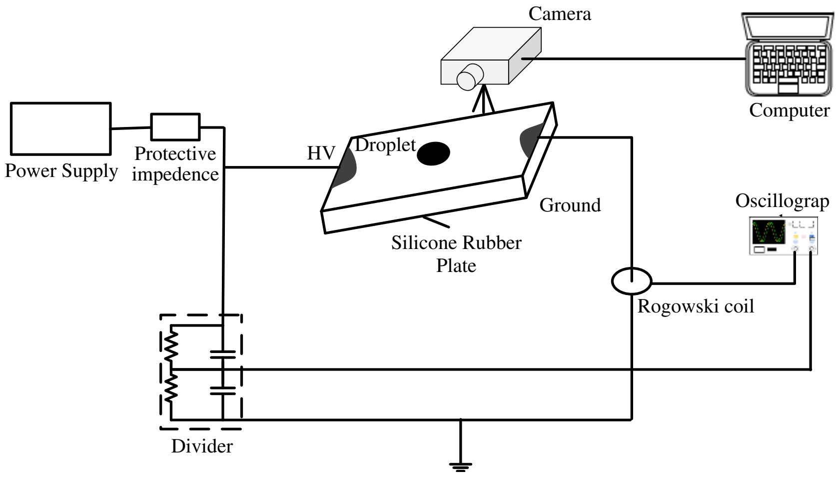


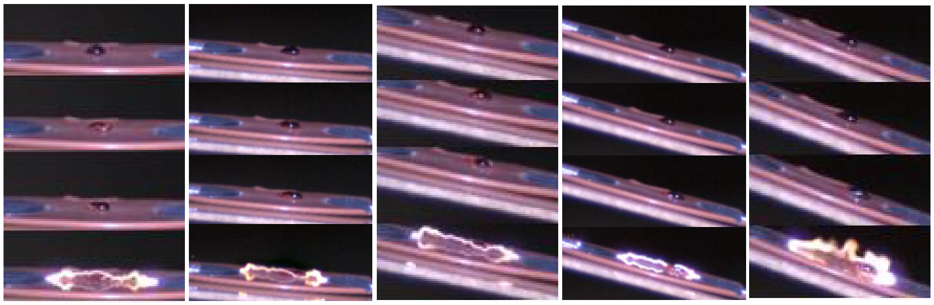
FIGURE 2. The platform of the AC flashover experiment.

Additionally, it was observed during the simulation that distinct configurations, characterized by pointed tips, appear at the upper section of water droplets near the lower end of the inclined surface during their motion. This paper believes that this is due to the influence of inertia on the dynamics of water droplets.

3. RESULTS AND DISCUSSION OF EXPERIMENTS

3.1. Experimental Platform and Measurement Method

An experimental platform was established to study the motion law of water droplets on the surface of inclined insulators. The measuring circuit is shown in Fig. 2. A certain volume of water droplet was taken by a microsyringe injector and injected in the middle between the two electrodes on both sides of the insulator sample, and a new water droplet was replaced after each flashover event. The sample was subjected to a continuously increasing voltage method, and each boost was 0.6 kV, withstanding 10 seconds. The flashover process was recorded by a high-speed camera (Phantom VEO 340L model, manufactured by VRI, USA), while the voltage and current signals during the flashover process were recorded by an oscilloscope (Tektronix DPO 2012B). The slope inclination was incremented in steps of 5°, and each inclination was repeated 10 times in the experiments. It is worth noting that the experimental specimens were locally cut from the surface of composite insulator skirts, with dimensions of 80 mm × 40 mm × 5 mm. The hydrophobicity grade of the specimens was CH2, and the conductivity of the



(a) (b) (c) (d) (e)

FIGURE 3. The results of the water droplet motion experiment.

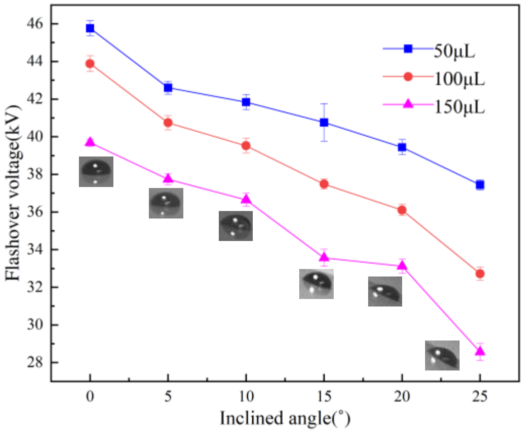


FIGURE 4. The relationship between AC flashover voltage and the inclination angle of the inclined plane.

water droplets was strictly prepared to match the characteristics of standard rainfall (100 µS/cm).

3.2. Experimental Results and Discussion under AC

Through multiple experimental investigations, it has been considered that the motion characteristics of water droplets on an inclined surface under AC electric fields primarily exhibit two distinct modes. When the inclination angle of the inclined plane is small, the water droplet oscillates left and right on the sample surface under the electric field. With an increase in the inclination angle, the oscillatory behavior becomes less pronounced. With increasing voltage, the water droplet elongates towards both sides relative to its initial position, as shown in Figs. 3(a) and (b). When the inclination angle of the inclined plane exceeds 10°, during the initial phase of voltage application, the top of the water droplet exhibits a slight but inconspicuous vibration. With the increase of voltage, the water droplet starts to elongate downwards along the inclined surface, as shown in Fig. 3(c). When the inclination angle of the inclined surface is large enough, the water droplet gradually slides and elongates along the surface, as shown in Figs. 3(d) and (e). It is worth noting that before flashover, the elongation phenomenon of water droplets on the inclined plane is more pronounced than the elongation on a plane with a smaller inclination angle.

By analyzing the motion law of water droplets on different inclined surfaces, it has been found that the elongation length of water droplets on the inclined surface is obviously greater than on a flat plane (with an inclination angle of 0°). On the flat plane, the water droplet exhibits regular oscillation left and right, while on the inclined surface, the motion water droplet is characterized by elongation in the downward direction along the inclined plane. Before the occurrence of flashover, the elongation of water droplets on the inclined surface is more pronounced than the flat plane. Moreover, when the inclination angle of the inclined surface is large enough, the water droplet not only elongates but also experiences some sliding. To investigate the influence of water droplet motion on flashover voltage, flashover voltage measurements were conducted through multiple experiments with different inclination angles. The relationship between the flashover voltage and inclination angle is shown in Fig. 4.

As can be seen from the curve in Fig. 4, the flashover voltage is significantly decreased with the increase of the inclination angle of the slope. This is because the elongation of water droplets on a flat surface is not very significant, so the flashover voltage is higher. The larger the inclination angle is, the greater the component of gravity is acting downwards along the slope. Under the influence of the electric field force and gravity, water droplets are more easily stretched. It is observed that when the volume of the water droplet reaches 150 µL after the inclination angle of the slope reaches 20°, the water droplets are stretched to some extent accompanied by slipping. As the water droplets slide downwards, water stains are left on the surface of the sample, which is actually equivalent to covering a layer of water film on the surface of the sample, further contributing to promoting the decrease of flashover voltage. In Fig. 4, when the inclination angle of the slope is increased from 20° to 25°, the decrease rate of the flashover voltage is greater than angles below 20°. This is due to the slipping and stretching of water droplets.

4. CONCLUSIONS

The motion behaviors of water droplets on the surface of insulators at different inclination angles by using a combination of simulation and experimental methods are investigated in this paper. The simulated and experimental results show that the motion modes and flashover phenomenon of water droplets differ under an AC electric field at different inclination angles of the insulating surface. Consequently, they also exhibit variations. The following conclusions are drawn in this paper:

(a) Under the AC electric field, the motion law of the water droplet shows different dynamic behaviors with the change of inclination angle of the inclined surface. The motion modes of water droplets can be summarized into three forms: oscillation, elongation, and slipping. When the inclination angle of the inclined surface is small, the water droplets oscillate left and right and elongate on both sides. With the increase of the inclination angle, the tendency of the water droplets to oscillate left and right weakens, and the motion of the water droplets is mainly elongating downwards along the inclined surface. When the inclination angle of the inclined surface is large enough, the water droplets will slip along the sample surface to some extent while stretching.

(b) The flashover voltage also shows a downward trend with the increase of the inclination angle of the inclined surface. Moreover, when the inclination angle is large, the water stains left by the slipping of the water droplets will also cause a rapid decrease in the flashover voltage along the surface.

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