Mechanisms and Influence Factors of Dynamic Behavior of Water Droplets on the Composite Insulator Surface under AC Electric Field

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Abstract—The deformation behaviors of a droplet on surface of composite insulator can strengthen local electric field, which could finally lead to flashover. Both experiments and numerical simulations for dynamic behaviors of a droplet on the surface of a composite insulator under applied AC voltage are investigated in this paper. Experiments are performed to study the influences of water droplet's volume and conductivity on dynamic behaviors. Two critical parameters are proposed to describe the morphological change process of water droplet, and it is shown that the process can be divided into three stages. Moreover, these motion laws are explained by establishing theoretical factors and physical influence models. In addition, we perform computer simulation to study the dynamic behaviors of a water droplet under AC field, and the findings are in good consistency with our experimental results, proving the rationality of the theoretical physical model. It is found that the vibration frequency of droplet changes regularly with at different stages under the AC electric field.

1. INTRODUCTION

In recent years, following the pace of the construction of ultra-high voltage (UHV) network projects, composite insulator has been developed rapidly. Because of their hydrophobic surface, composite insulators with silicone rubber sheds have a higher flashover voltage than conventional insulators under contaminated conditions [1].

The description of dynamic behavior of water droplets on the surface of a composite silicone rubber and its influencing factors have been the subject of extensive experimentation. Different dynamic behaviors of water droplets on insulator surface such as the deformation and fusion of water droplets can affect flashover voltage by changing the distribution of the electric field [2–7]. Moreover, dynamic behavior is affected by the hydrophobicity of insulating materials as well as the volume, conductivity, and charge of water droplets [2–4, 7–9]. Under AC electric field, the motion and deformation of water droplets are regular, and the vibration frequency of water droplets is different due to the influence of various factors such as the volume and charge of the water droplets. The research in [5, 6, 8, 9] shows that due to different volumes and charges, the vibration frequency of water droplet is one or two times of the frequency of the applied voltage, unlike in [10] which shows that it is a half.

Despite a vast literature concerned with the experimental characterizations of influence factors of the dynamic behavior of water droplets on composite insulator surface, little is known about the detailed information behind it, especially a quantitative description accounting for it. In what follows we present general motion laws describing a water droplet dynamic behavior under AC electric field quantitatively with consideration of the influences of its volume and conductivity to analyze our experimental data. In addition, we perform computer simulation to study the dynamic behaviors of a water droplet under

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AC field, and the findings are in good consistency with our experimental results, proving the rationality of our theoretical model.

2. SAMPLE AND PLATFORM OF EXPERIMENT

The experimental setup for monitoring a single water droplet dynamic behavior under AC electric field is shown in Fig. 1. The initial AC voltage over the sample is applied by a voltage step-up method at a $0.6\,\mathrm{kV}$ boost with a duration of 10 seconds each time step until discharge occurs. Then the voltage applied over the sample is changed to $0.3\,\mathrm{kV}$ boost with a duration of 10 seconds each time step until flashover. The whole dynamic process of a droplet is recorded by the high-speed camera with $1000\,\mathrm{FPS}$ [11, 12].
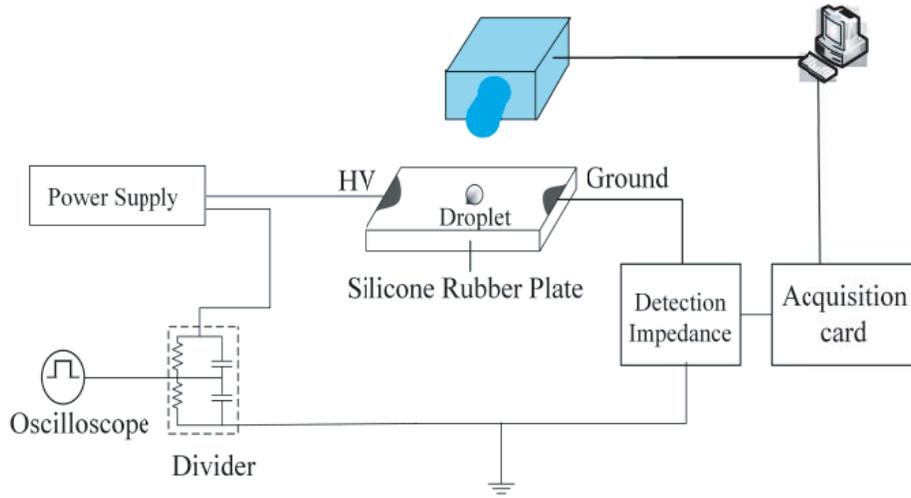
Figure 1. The principle of the experiment.

The initial contact angle of the droplet is about $80°$; the size of the silicone rubber plate sample is $100 * 50 * 10$ (mm); and the minimum distance between the two electrodes is $50\,\mathrm{mm}$. In order to investigate the effect of the conductivity and volume on the law of the water droplet movement, we perform our experiment on water droplet samples with the same conductivity ($100\,\mathrm{\mu S/cm}$) but different volumes of 50, 100, 150, 200, and $150\,\mathrm{\mu L}$ and with the same volume (NaCl solution with a volume of $100\,\mathrm{\mu L}$) but different conductivities of 30, 100, 500, 1000, and $8000\,\mathrm{\mu S/cm}$, respectively.

3. THE EXPERIMENTAL RESULTS AND THEORETICAL ANALYSIS

3.1. The Dynamic Behaviors of Water Droplet under AC

By characterizing the movement of water droplet from the initial stage of pressurization to the preflashover stage, we divide the dynamic behavior of water droplet under AC step-on voltage into three stages, as shown in Fig. 2. Namely, the first stage is the oscillation on the top of the water droplet at the beginning of pressurization as depicted in Fig. 2(a); the second stage is the clear peak and valley of the water droplet in the middle of pressurization as presented in Fig. 2(b); and the third stage is the obvious left-right oscillation of the whole water droplet before the flashover, as shown in Fig. 2(c).

First, when the voltage rises to the critical value of the movement, oscillation begins to appear on top of the water droplet. By analyzing the image sequence of high-speed camera frame by frame, we find that the frequency of the oscillation is twice the frequency of applied voltage, and the direction is not a single left-right but a complex mode in all directions. With the increase of applied voltage, the amplitude of this oscillation increases, and the whole water droplet turns into a clear peak and

(a)

(b)

(c)
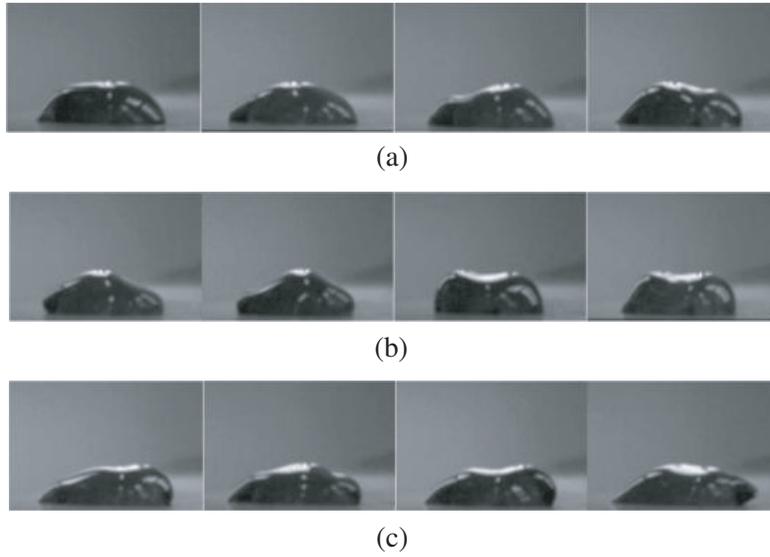
Figure 2. Three stages of water droplet motion under the AC field. (a) The first stage. (b) The second stage. (c) The third stage.

valley state in the second stage. It should be noted that the oscillation frequency in the second stage is still approximately twice the frequency of applied voltage. Finally, as the voltage rises to the critical flashover value, the frequency of the left-right oscillation of the whole water droplet becomes the same as the frequency of the applied voltage.

3.2. Numerical Analysis of the Mechanism of Water Droplet Dynamic Behavior

Figure 3 shows the force diagram of the water droplet on the insulator surface under electric field. G and N represent gravity and support force, respectively. F_e is the body force of water droplet under the electric field, consisting of Maxwell stress, Coulomb force, and electric field gradient force. F_{st} is the surface tension on interface between water droplet, silicon rubber plate, and air, consisting of γ_{gl} (gas-liquid interface), γ_{sl} (solid-liquid interface), and γ_{sg} (solid-gas interface).
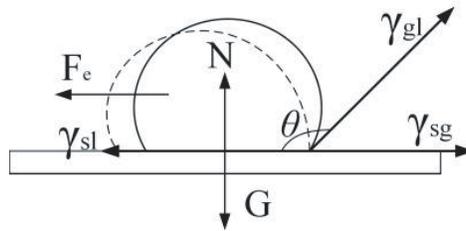
Figure 3. The force diagram.

The equation of water drop movement on the surface of a composite insulator under electric field can be obtained by Navier-Stokes (N-S) equations:

$$\rho \left[\frac{\partial u}{\partial t} + (u \cdot \nabla)u \right] = \nabla \cdot (-PI) + \nabla \left[\mu \left(\nabla u + (\nabla u)^T \right) \right] + \rho g + F_{st} + F_e \tag{1}$$

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

where u and ρ are the fluid velocity and mass density, respectively. μ is the fluid kinematic viscosity,

and g is the gravitational force density. Scalar P represents the pressure, and vector I represents the unit tensor, thus $((-PI)$ is the normal stress tensor. $\mu(\nabla u + (\nabla u)^T)$ is the shear stress tensor.

In the initial stage of pressurization, the free charge in the water droplet is ignored. According to the principle of virtual work, the force of the uncharged liquid under the action of the electric field is expressed by [13]:

$$F'_e = \nabla \cdot T + \frac{1}{6}\nabla \left[E \cdot E\varepsilon_0 \left(\varepsilon_r - 1\right)\left(\varepsilon_r + 2\right)\right] \tag{3}$$

where Maxwell stress tensor $T = ED^T - 0.5(E \cdot D)I$, and E and D are electric field strength and electric flux density, respectively. Maxwell tensor of the second-order can be written as:

$$T_{ij} = \varepsilon_0\varepsilon_r \left(E_iE_j - \frac{1}{2}\delta_{ij}E^2\right) \tag{4}$$

where ε_0 is the vacuum permittivity, and ε_r is the relative permittivity of water. The subscripts i and j define the direction of the electric field in the two-dimensional plane. $\delta_{ij} = 1$ when $i = j$ and $\delta_{ij} = 0$ when $i \neq j$.

The second term on the right side of Equation (3) indicates that the electric field gradient force caused by the degree of electric field is inhomogeneity, and its effect is negligible which be ignored in the analysis of this paper.

As a strong polar material, water molecules tend to polarize at the applied electric field. Therefore, the electric field force of the droplet in the initial stage of pressurization is mainly governed by Maxwell's stress, which is proportional to the square of the field strength, as shown in Equation (4). As a result, the force caused by Maxwell stress can be written as:

$$F'_e = \nabla \cdot T \propto (E\sin\omega t)^2 = \frac{1}{2}E^2\left[1 - \cos\left(2\omega t\right)\right] \tag{5}$$

where $E\sin\omega t$ is the sinusoidal electric field caused by the applied voltage. Therefore, the droplet oscillates with twice the frequency of applied voltage at the initial stage of pressurization.

Figure 4 shows the schematic of the electric field force on the water droplet during the initial stage of pressurization. For the AC electric field, in the positive half cycle, the polarization charges distribution, and the direction of electric field force is shown in Fig. 4(a). At the beginning of the negative half cycle, the direction of the electric field changes instantaneously. However, due to the influence of dielectric relaxation, the distribution of the polarization charges cannot be changed in time as shown in Fig. 4(b). Fig. 4(c) shows the final equilibrium charge distribution after a short period of relaxation. This process leads to the complexity of the dynamic behavior of water droplet, and it may be the cause of the peak-valley shape of water droplet in the second stage, which is also proved by our later simulation.
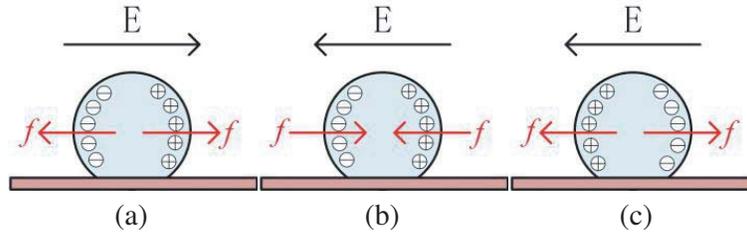
Figure 4. The schematic of the electric field force.

In the first stage, the polarization force is so small that the motion only occurs at top of the droplet. With the increase of applied voltage amplitude, the motion of water droplet develops to its second stage, in which the whole droplet appears in peak and valley shape. The further increase of voltage leads to corona discharge. In this stage, the severe distortion of the electric field at the triple-point produces a tremendous number of space charges, leading to the injection of a large number of free charges into the

water droplet. Therefore, the electric field force should be rewritten as:

$$F'_e = \nabla \cdot T + \frac{1}{6}\nabla\left[E \cdot E\varepsilon_0(\varepsilon_r - 1)(\varepsilon_r + 2)\right] + QE \tag{6}$$

where Q is the free charges injected by corona discharge in the water droplet, and QE is the Coulomb force. When the applied voltage reaches a certain critical value, the electrode force can be ignored, thus the Coulomb force plays a leading role [9]. The Coulomb force is proportional to the electric field, so the droplet is expected to oscillate with the same frequency as the applied voltage in the third stage of pressurization.

3.3. Influence of Water Droplet Volume and Conductivity on Dynamic Behavior

Figure 5 shows the effect of the AC electric field on the dynamic behavior of water droplet. The dotted black line represents the starting voltage of double frequency oscillation (U100), which is the critical voltage when the water droplet enters the first stage of movement, changing with the conductivity, while the solid red line represents the starting voltage of power frequency oscillation (U50), which is the critical voltage when the motion enters the third stage, changing with the conductivity. It can be seen that with the increase of conductivity, U100 is changed significantly, while U50 first decreases and then increases.
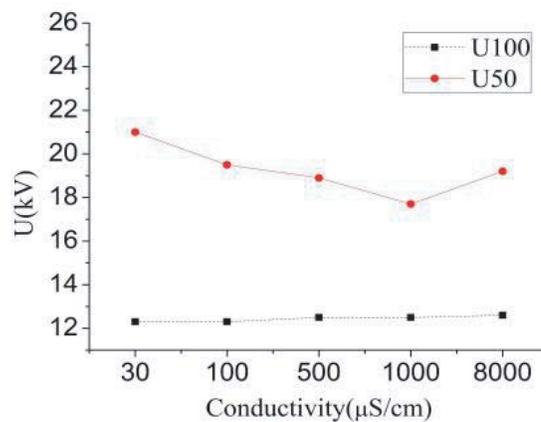
Figure 5. The effect of conductivity on the dynamic behavior.

As stated above, electric field polarization force accounts for the double frequency vibration of water droplet under the AC electric field, and it depends on the field strength and permittivity of droplet, so U100 does not change significantly with the increase of conductivity.

The power frequency vibration of the droplet depends on the Coulomb force determined by the field strength and free charges in the droplet. The electric field, especially at the triple-point, increases with the increase of droplet conductivity. This implies that the motion will enter the third stage at a relatively lower applied voltage. However, the conductivity of water droplets is positively related to the amount of soluble inorganic salt on the surface pollution layer of an insulator and the concentration of a large number of soluble salts and inorganic acid ions in fog, dew or rain water [14, 15]. The surface tension, which dominates the shape of the droplet, increases with the concentration of inorganic acid, alkali, salt, and other solutes [16]. Therefore, the starting voltage of U50 will rise when the conductivity reaches a critical value.

Fig. 6 shows the correlation between applied voltage and the volume of water droplet, where solid red line is for U50 and dotted black line for U100, respectively. The increasing rate of U50 with volume is more significant than that of U100 as shown in Fig. 6.

Under the AC electric field, the increase of water droplet volume requires a bigger electric field force for breaking the original static equilibrium state. Therefore, both U100 and U50 are increased with the volume of droplet. According to the literature [9], the larger the size of water droplets is, the
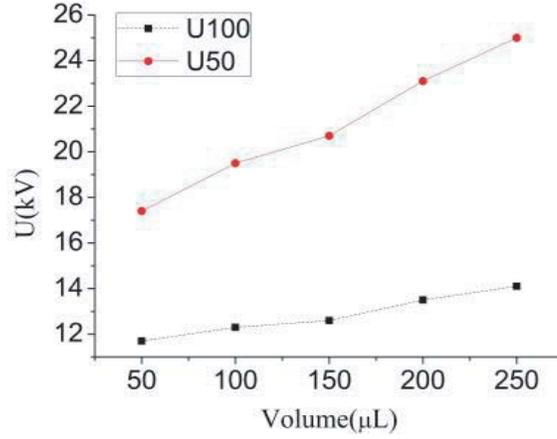
Figure 6. The effect of volume on the dynamic behavior.

more charges are needed to change the vibration from double frequency to power frequency, while in the case of constant charges, the larger volume requires a larger electric field for the conversion of motion frequency. This is also in line with our conclusion.

4. COMSOL MODELING AND SIMULATION

4.1. Multi-field Modelling

In order to confirm the above theoretical analysis, we simulate the dynamic behavior of water droplets under AC electric field by using commercial finite element software COMSOL Multiphysicis. The dynamic behaviors of a droplet under the electric field are modeled and calculated using Navier-Stokes equations in this paper. It describes the fluid motion as well as tracks the interfaces between the immiscible fluids. In addition, we solve the electric quasi-static field equation for the electric field calculation.

The Maxwell's equations are reduced to the electroquasistatic (EQS) equations:

$$\sigma \nabla \cdot E + \varepsilon \frac{\partial}{\partial t} \nabla \cdot E = 0 \tag{7}$$

$$E = -\nabla \varphi \tag{8}$$

where φ is the scalar potential; E is the electric field vector; ε and σ are permittivity and conductivity, respectively.
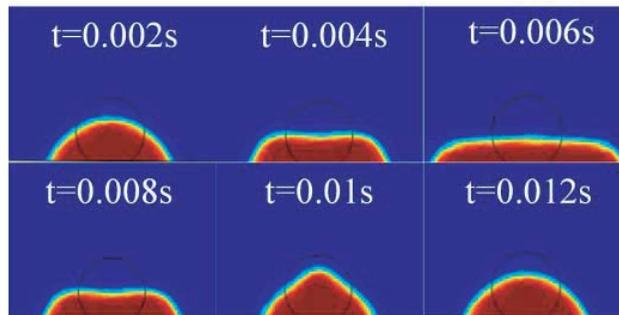
Figure 7. The dynamic behavior caused by Maxwell stress.

The interface between the water droplet and air, a two-phase flow problem, is described by the incompressible Navier-Stokes (NS) equations shown in Equations (1) and (2).

By coupling EQS equations and NS equations, the simulation of dynamic behavior of water droplet is performed in COMSOL Multiphysics.

In the initial stage of pressurization, the free charges in the water droplet are ignored, and the dynamic behavior is only affected by the polarization force. Therefore, the electric field force of N-S equations is expressed by the divergence of Maxwell stress tensor in the coupling computation model.

Figure 7 shows the dynamic behavior of water droplet under the AC electric field. The simulation is initialized by applying a high AC electric potential with a frequency of 50 Hz to the left electrode and grounding the right electrode.

4.2. Analysis of Simulation Results

During the stretching process, a wave trough appears first and then stretches to a certain length until converging in the middle, resulting in a wave peak. Finally, the water droplet recovers to its original shape, and the whole process repeats periodically. Each vibration cycle in our simulation is 0.01 s, which is twice of the power frequency. These calculation results are in accordance with our experimental data. As the pressurization time increases, this dynamic behavior becomes more obvious, leading to a complex dynamic behavior in the second stage.

We introduce negative charges to the water droplet in our simulation by setting the initial condition of electric field. Fig. 8 shows the simulation results by introducing Coulomb force in the third stage. The dynamic behavior of water droplet appears in a left-right oscillation mode with the same frequency as the power frequency, which is also consistent with the experimental results.
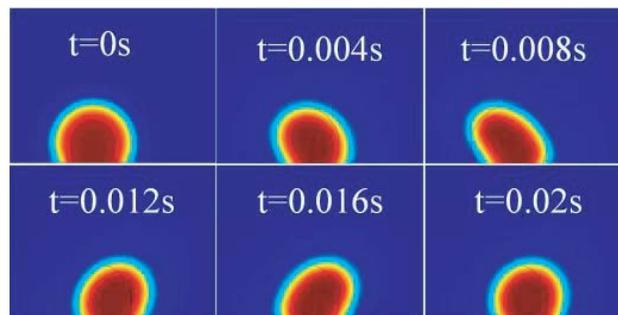
Figure 8. The dynamic behavior caused by Coulomb force.

Water droplet on the surface of composite insulator shows interesting dynamic behaviors under AC electric field. However, we still face some challenges, e.g., how to relate these dynamic behaviors to flashover, which is crucial for understanding the flashover mechanism of a composite insulator.

5. CONCLUSIONS

In the present work, we have numerically and experimentally investigated the dynamic behavior of a single water droplet on composite insulating surface subjected to AC electric field, using a phase field computational method. The difference in the dynamic behaviors of the water droplet on common silicone rubber can be attributed to force balance, polarization of water, and electric field alternation. More importantly, the motion laws for the dynamic behaviors of water droplet under AC field are presented, and the mechanisms behind its dynamic behavior are explained quantitatively by principles of physics. The results can be summarized as follows:

(a) Under AC electric field, the initial stage of the pressurization of the irregular oscillation occurs at the top of the water droplets caused by the polarization force, and its frequency is twice the power frequency.

(b) With the increase of applied voltage, the oscillation on the top of the water droplet gradually develops into the oscillation of the whole water droplet that has a distinct peak and valley phenomenon. It is worth noting that in the second stage, the oscillation frequency of the water droplet is still twice the frequency of applied voltage.

(c) With the further increase of applied voltage, the field enhancement leads to a large number of space charges produced by corona discharge, and the water droplet is affected by space charges and oscillates at the same frequency as the applied voltage under the action of Coulomb force.

(d) We present general motion laws of a water droplet under AC electric field with consideration of the influences of its volume and conductivity concluded by our experimental study. The increase of water droplet volume makes both the starting voltages of double frequency oscillation and power frequency oscillation increase, while the increase of water droplet conductivity makes the starting voltages of power frequency oscillation decrease first and then increase, but has little effect on the starting voltages of double frequency oscillation.

However, the mechanism of water droplet's dynamic behavior to influence the flashover voltage needs to be revealed in our future works, which is crucial for understanding the flashover mechanism of a composite insulator.

ACKNOWLEDGMENT

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