The effect of dynamic behaviours of the water droplet on DC/AC flashover performance on silicone rubber surface: Experiment, simulation and theoretical analysis

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Abstract
It is usually seen that DC flashover voltage of the water droplet on the surface of silicone rubber (SIR) composite insulator is lower than AC flashover voltage. It is necessary to study the mechanisms and influencing factors of the surface properties. In this article, experiments are performed to study the moving processes of the water droplet and the influences of its dynamic behaviours on flashover voltage under DC/AC electric field. Besides, an electrohydrodynamic coupling method is employed to establish the simulating model. Moreover, the theoretical physical model is established to reveal the mechanisms of dynamic behaviours of a droplet. It is indicated that the simulation results are in good consistency with the experimental data. The elongation behaviours of a droplet on the surface of a composite insulator can influence the homogeneity of the electric field distribution along the sample's surface. It is shown that the different dynamic behaviours and flashover performances for a single water droplet on the SIR surface are both affected by the volume of the droplet and the type of voltage applied.

1 | INTRODUCTION

Understanding the dynamic behaviour of water droplets is helpful to the efficient manipulation of low-volume droplets. Microfluidic devices based on electrohydrodynamics has great potential in the field of biochemical testing and industrial applications [1,2]. However, the existence of water droplets also has a certain impact on the external insulation in power system [3–5]. In recent years, with the increasing construction of ultra-high voltage (UHV) network projects, the composite insulators are widely used. Because of their hydrophobic surface, composite insulators with silicone rubber (SIR) sheds have a higher flashover voltage than conventional insulators under contaminated conditions [6,7]. In the UHV transmission lines that have been running, the consumption of composite insulators is as high as 85% in China [8]. However, different from the water film on the surface of classic porcelain and glass insulator, the moisture will exist in the form of separated water droplets on composite silicone rubber insulators in wet weather conditions such as rain, fog and dew. Therefore, the traditional flashover mechanisms of porcelain and glass insulator are no longer suitable for silicone rubber insulation materials [9].

When the hydrophobic surface of the polymeric insulator is moistened by fog or rain, water droplets are formed. Investigations based on the influence of water droplets on the performance of a polymeric insulator were carried out. The presented studies for the motion of droplets under the impact of an alternating electric field is well known in [10–16]. Moreover, the dynamic behaviour is affected by the hydrophobicity of the insulating materials as well as the volume, conductivity and charge of water droplets [17–22]. Under the AC electric field, the vibration frequency of the water droplets is different due to the influence of various factors such as the volume and charge of the water droplets [23–25]. It is generally believed that the motion laws of the water droplets are relatively simple under the DC electric field. The research in [10] shows that the droplet elongation occurs somewhat stepwise due to contact angle hysteresis. The research conducted under the DC electric field in [17] shows that the water droplet will move in the opposite direction of the electric field due to the accumulation of negative charges.
The existence of water droplets on the surface of composite insulators could cause a reduction of the DC and AC flashover voltage [18]. Generally, different dynamic behaviours of the water droplets on insulator surfaces such as the deformation and fusion of water droplets can affect the distribution of the electric field [17–19]. The existence of water droplets will influence the homogeneity of the electric field distribution along the insulator surface and cause onset surface discharge at the triple junction of the SIR surface, the water droplet and air. When the electric field reaches the critical ionization field in air, corona discharge can take place and this induces an occurrence of air breakdown and even surface flashover [18].

However, the relationship between dynamic behaviours and flashover mechanisms of the water droplets formed on hydrophobic composite materials has not been sufficiently and quantitatively investigated. This article is focussed on describing dynamic behaviours of a water droplet and the consideration of its influence on the flashover voltage under DC/AC electric field. In addition, the electric-field distributions and dynamic behaviours that affect the flashover performance are analysed by means of computer simulation and related experiments.

2 | EXPERIMENTAL SYSTEM

2.1 | Sample and platform of experiment

The experimental setup for monitoring the dynamic behaviour of a single water droplet under both DC and AC electric field is shown in Figure 1, including a DC/AC high voltage supply (100 kV, 50 kVA) and a high-speed camera (10,000 frames maximum). The initial voltage over the sample is applied by a voltage step-up method at a 0.6 kV boost with a duration of 10 s for each timestep until a morphological change of the water droplet occurs. Then, the voltage applied over the sample is changed to 0.3 kV boost with a duration of 10 s at each timestep until flashover. In this work, the speed of the camera used for recording is 1000 frames/s [26].

As shown in Figure 2, the silicone rubber plate of a sample in this experiment is made of the silicone rubber insulator shed. The half elliptical electrode made of copper is tightly bonded with the silicone rubber to avoid partial corona discharge. The size of the silicone rubber plate is 100 × 50 × 10 mm, the radius along a major axis of an elliptical electrode is 15 mm, the radius along the minor axis is 10 mm, the thickness of electrode is 1.5 mm, and the distance between the two electrodes is about 80 mm.

In order to investigate the effect of the volume on the movement of water droplets, the water droplet samples are made of NaCl solution with a constant conductivity (100 μS/cm) for various volumes of 50, 100, 150, 200 and 150 μl, respectively. The initial contact angle of the droplet is about 90°.

2.2 | The parameters to describe the dynamic behaviour of droplet

In order to express the influence of the dynamic behaviours of water droplets on the flashover of insulator more clearly, two

\[ \theta_n = (\theta_1 - \theta_2)/\theta_0 \]  

where \( \theta_0 \) is the initial contact angle, \( \theta_1 \) is the contact angle close to the left side of HV electrode, and \( \theta_2 \) is the contact angle close to the right side of the ground electrode.

The absolute value of \( \theta_n \) reflects the degree of the water droplet deformation. In addition, the value of \( \theta_n \) is positive when the water droplet is stretched to the HV electrode, and negative to the grounding electrode.

As shown in the Figure 4, the elongation factor is defined as \( L_n \), which describes the change rate of contact length between the water droplet and the silicone rubber plate, which can be written as:

\[ L_n = (L - L_0)/L_0 \]  

where \( L_0 \) is the contact length between the water droplet and the silicone rubber plate in the initial state, and \( L \) is the contact length between them when the water droplet is stretched by a DC electric field.
3 | THE EXPERIMENTAL RESULTS AND THEORETICAL ANALYSIS

3.1 | The flashover phenomenon under DC and AC

As shown in Figure 5, the DC flashover voltage of a single water droplet on the surface of composite insulators is lower than the AC flashover voltage. Each flashover test was repeated for 10 times. With the increase of volume, both AC and DC flashover voltage show a decreasing tendency. It is shown that the DC flashover voltage decreases with larger gradient and has bigger standard deviations than AC flashover voltage. In Figure 6, the two-dimensional Weibull distribution is in fairly good agreement with experimental results.

It is considered that the causes of the difference between DC and AC flashover voltage are related to different dynamic behaviours of the water droplet. The dynamic behaviours of a single water droplet under DC and AC electric field are quite different.

3.2 | The deformation factor and elongation factor under DC and AC

The two mentioned parameters (elongation factor $L_n$ and deformation factor $\theta_n$ of the water droplet) are analysed according to the experimental results. The dependences of the two parameters on the applied voltage and the water droplet's volume under DC/AC voltage application are shown in Figures 7 and 8, respectively. It can be seen that the deformation factor decreases with the volume, while the elongation factor increases accordingly. It can be drawn from Figures 7 and 8 that the gradient of the water droplet elongation factor under DC is larger than that under AC, and the maximum value of the elongation factor for the water droplet at a certain volume under DC is also larger than that under AC.

The non-negative value of deformation factor $\theta_n$ means that the water droplet moves towards the opposite direction of the electric field. Zero values appear several times in Figure 7a, which is called the 'Recovery' phenomenon of a droplet under DC electric field. From the experimental results, when the water droplet reaches the critical state, the contact angle $\theta_1$ is 120°, and $\theta_2$ is about 30°, so that the maximum value of deformation factor $\theta_n$ is about 1. Now, the water droplet will be elongated to a maximum extent. Under AC electric field, the value of deformation factor fluctuates around zero, indicating that the water droplet moves left and right, as shown in Figure 7b.

Figure 9 shows the dependence of maximum elongation factor on the water droplet's volume under DC/AC voltage. It can be seen from Figure 9 that the maximum elongation factor under both DC and AC shows an increasing tendency with the increase in the volume of the water droplet. Associated with Figure 5, it is considered that the causes of the difference between the AC and DC flashover voltage are related to different elongation of the water droplet. There are two points for us to study. The first one is why the water droplet moves in the way as shown in Figures 7 and 8, while the second one is how the elongation of the water droplet affects the flashover.

3.3 | The dynamic behaviours of the water droplet under DC

According to the experimental results, the mechanism of the dynamic behaviour for the water droplet under the DC electric field is analysed in this section.
The experimental results show that an initial state of the water droplet is a semi-elliptical shape, as shown in Figure 10a. Then, we divide the movement process of the water droplet under DC voltage into three stages [26], as shown in Figure 10b–d.

In the first stage, the water droplet will stretch towards the opposite direction of the electric field when the applied E-field reaches a critical value, as seen in Figure 10b. During this stage, the deformation factor $\theta_n$ will increase, but the elongation factor $L_n$ will remain the same.

In the second stage, the ‘Recovery’ phenomenon, which makes the water droplet deflect in a certain direction and then return to the initial shape, is obtained. This ‘Recovery’ phenomenon does not exist only one time but occurs repeatedly. Before ‘Recovery’, the water droplet stretches towards the opposite direction of the electric field, as shown in Figure 10c. After ‘Recovery’, the shape of the water droplet is similar to the initial state in Figure 10a.

In the third stage, as the applied voltage continues to rise, the bottom edge of the water droplet will suddenly move and gradually stabilise in a new position, as shown in Figure 10d. When the water droplet stretches to the critical value, the absolute value of deformation factor $|\theta_n|$ reaches the maximum. Meanwhile, the elongation factor increases, and the contact distance between the water droplet and silicone rubber increases until flashover.

Finally, when the applied DC voltage reaches a critical value, the water droplet stretches in the opposite direction of the applied electric field. Finally, it causes a flashover, as shown in Figure 10e. The arc connects the two poles running through the surface of the water droplet and the silicone rubber plate.

For the single water droplet in the electric field, there are two main charges consisting of the electric field force, polarization charges and net space charges. The Coulomb force acts due to the net charges of a droplet. The Maxwell stress results from the polarization of the water. Figure 11a shows the

**Figure 7** The influence of water droplet's volume and applied voltage on the Deformation factor

**Figure 8** The influence of the water droplet's volume and applied voltage on the Elongation factor
schematic diagram of the electric field force of polarization charges on the water droplet. The water droplet will be stretched to both sides under the action of Maxwell stress $f_1$ and $f_2$ for polarization charges, which makes the elongation factor of the water droplet larger. Figure 11b shows the schematic diagram of the electric field force on the net negatively charged water droplet. When the net free charges reach an absolute critical value, the Coulomb's force plays a leading role [22]. The water droplet will be stretched to the opposite direction of the applied electric field under the action of Coulomb's force $f_3$, which makes the deformation factor of water droplet larger, as shown in Figure 11b.

According to the principle of virtual work, the force on a unit volume of the charged liquid under the action of the electric field caused by both Maxwell stress and Coulomb's force can be written as:

$$F_e = \nabla \cdot T + \frac{1}{6} \nabla (E \cdot E_0 (\varepsilon_r - 1)(\varepsilon_r + 2)) + qE$$

where, $\nabla$ is the nabla operator, $\varepsilon_0$ is the vacuum permittivity and $\varepsilon_r$ is the relative permittivity of water droplet. Maxwell stress tensor $T = ED^T - 0.5(E \cdot D)I$. $E$ and $D$ are the electric field strength and the electric flux density, respectively. The Maxwell stress is proportional to the square of the field strength $|F| \propto E^2$. The second term on the right side of Equation (3) indicates that the electric field gradient force caused by the degree of an electric field is inhomogeneous, which is ignored in the analysis of this article. $q$ is the free

**Figure 9** The dependences of the elongation factor on the volume of the water droplet under DC/AC voltage.

**Figure 10** The dynamic behaviours of the water droplet under DC.

**Figure 11** The schematic diagram of the electric field force under DC.
charge in the unit volume of water droplet, and \( qE \) is the Coulomb's force. The force due to net charges is directly proportional to the electric field \( |F| \propto E \).

The mechanism of the dynamic behaviours of the water droplet under the DC electric field is presented in Figure 12, in which the direction of the applied electric field is horizontal to the right.

Once the DC voltage is applied, the water molecules are polarized by the electric field in Figure 12a. The electric field forces due to bound charges are in equilibrant that keeps the balance of the droplets. Both the elongation factor and the deformation factor of the droplet are small.

In the first stage, a large number of negative charges are accumulated in the water droplet due to the injection of free electrons as depicted in Figure 12b. There are several ways for a droplet to obtain a net charge. Free electrons produced by ionizing air at the boundary between water droplet, silicone rubber plate and air \([23,24]\) can be absorbed by the water droplet, which is electronegative. Then the directional motion of this negative charge under the DC field causes the water droplet to stretch in the opposite direction of the applied electric field as shown in Figure 12c. The electric field forces due to bound charges \( f_1 \) and \( f_2 \) are not in equilibrant, and the joint force of these two forces is to the left.
In the second stage, the deformation of the droplet appears to have a tip with a large curvature on the top of a droplet, where the electric field is further distorted, and the air ionization will be caused, as shown in Figure 12d. The net negative charges inside the water droplet will be neutralised with positive anions generated at the droplet tip with electric field distortion. The electron emitted at the tip of the droplet will dissipate as it moves towards the positive pole or when absorbed by the oxygen atom in the air to generate negative oxygen anions. Thus, the droplet without net free charges will return to the initial state in Figure 12c. This ‘Recovery’ phenomenon takes place in a cycle of 5 ms for several times. The deformation factor of the water droplet becomes up and down, while the elongation factor continues to grow larger.

In the third stage, when the water droplet continually stretches to a critical value in Figure 12f, the absolute values of the deformation factor and elongation factor reach the maximum.

### 3.4 The dynamic behaviours of the water droplet under 50 Hz AC

According to the experimental results, the mechanism of dynamic behaviour for water droplets under AC electric field is analysed in this section. By characterising the movement of the water droplet from the initial stage of the voltage application to the pre-flashover stage, we divide the dynamic behaviours of the water droplet under AC step-on voltage into three stages [26], as shown in Figure 13. In the first stage, there is the subtle high-frequency oscillation on the top of the water droplet at the beginning of voltage application as depicted in Figure 13a. In the second stage, there is the apparent peak and valley of the water droplet in the middle of voltage application as presented in Figure 13b, while in the third stage, there is the obvious left-right oscillation of the whole water droplet before the flashover, as shown in Figure 13c.

First, when the voltage rises to the critical value of the movement, the top of the water droplet begins to appear subtle at a high-frequency oscillation. Further analysis shows that the high frequency of the subtle 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 local subtle high-frequency oscillation increases, and the whole water droplet turns into a clear peak and 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 the 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.

Figure 14 shows the schematic of the electric field force on the water droplet during the initial stage of voltage application. For the AC electric field, in the positive half cycle, the distribution of the polarization charges and direction of electric field force $f$ are shown in Figure 14a. At the beginning of the negative half cycle, the direction of the electric field changes instantly. However, due to the influence of dielectric relaxation, the distribution of the polarization charges cannot be changed promptly as shown in Figure 14b. Figure 14c shows the final equilibrium charge distribution after a short period of relaxation. This process leads to the complexity of the dynamic behaviour of the water droplet and it may be the cause of the peak-valley shape of water droplet in the second stage.

In the first stage, the polarization force is so small that the motion only occurs at the top of droplet. Thus, the amplitudes of the deformation factor and the elongation factor are both small. With the increase in the applied voltage amplitude, the motion of water droplet develops to the second stage. When the applied voltage reaches a certain critical value, the electrode force can be ignored; thus the Coulomb force plays a leading role [22]. The Coulomb force is proportional to the electric field, so the amplitude of deformation factor and elongation factor shows increasing tendency with an increase in E-field strength.

### 4 NUMERICAL SIMULATION

In this section, the motion process of water droplet and the real-time electric field distribution are numerically calculated by the finite element method to analyse the relationship between the dynamic behaviours of droplet and the electric-field strength on insulator surface.

#### 4.1 Multi-field modelling

For the numerical study, commercial finite element software COMSOL Multiphysics is used in this article [27,28]. The dynamic behaviours of a droplet under the electric field are modelled and solved in a 2D domain by the Navier–Stokes equation, including the term sources of water/air interfacial tension, the gravity force and the electric force. The phase-field equations are used for the interface capturing. One droplet is placed at the centre of the computational domain. The no-slip boundary condition was used at the solid. In addition, we solve
the electric quasi-static field equation for the electric field calculation.

The Maxwell’s equations are reduced to the electro-quasi-static (EQS) equation:

\[
\sigma \nabla \cdot \mathbf{E} + \varepsilon \frac{\partial}{\partial t} \nabla \cdot \mathbf{E} = 0
\]

(4)

\[
\mathbf{E} = -\nabla \varphi
\]

(5)

where \( \varphi \) is the scalar potential, \( \mathbf{E} \) is the electric field vector, and \( \varepsilon \) and \( \sigma \) are permittivity and conductivity, respectively.

A two-phase flow problem, at the interface between water droplet, silicone rubber plate and air, is described by the incompressible Navier–Stokes (NS) equations [23]:

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\text{Re}} \mathbf{F}_u + \mathbf{F}_\mathbf{e} + \nabla \cdot \mathbf{F}_\mathbf{v}
\]

(6)

\[
\nabla \cdot \mathbf{u} = 0
\]

(7)

where \( \mathbf{u} \), \( \rho \) and \( p \) are the fluid velocities, pressure and mass density respectively, \( \mathbf{u} \) is the fluid kinematic viscosity, and \( g \) is the gravitational force density. \( \mathbf{F}_u \) is surface tension. Scalar \( p \) represents pressure, and vector \( \mathbf{I} \) represents unit tensor. Thus \( (-\mathbf{I}) \) is the normal stress tensor, and \( \mathbf{u}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \) is the shear stress tensor.

By coupling EQS equations and NS equations, the simulation of dynamic behaviours of water droplets is performed in COMSOL Multiphysics. The material properties used in the simulations are listed in Table 1 [16].

All variables are required to converge to a tolerance of \( 5 \times 10^{-3} \). Concerning the mesh, free triangular meshing is used in the whole domain. The smallest element size is \( 4 \) \( \mu \text{m} \), and the largest one is \( 280 \) \( \mu \text{m} \). The simulations are initialised with the application of an electric potential to the left electrode when the right electrode is grounded. The electric potential of HV electrode is set to 30 kV for both DC and 50 Hz AC.

The distance between the two electrodes is 100 mm. The water droplet volume is 100 \( \mu \text{L} \), and the static contact angle chosen is 90°.

| TABLE 1 Material properties for simulation |
|-------------------------------------------|
| Material Properties | Water | Air | Solid |
|---------------------|------|-----|------|
| Density (kg/m\(^3\)) | 1000 | 1   |      |
| Viscosity (Pa.s)    | 0.89 \times 10^{-3} | 1.83 \times 10^{-5} |
| Interfacial tension (N/m) | 0.073 |
| Relative permittivity | 81   | 1   | 3.6  |
| Conductivity (\(\mu\text{S/cm}\)) | 5.5  | 5.5 \times 10^{-9} | 10^{-8} |

force of N-S equations is expressed by the divergence of Maxwell stress tensor in the coupling computation model.

We introduce negative charges to the water droplet in our simulation by setting the initial condition of electric field. The value of space charge density is \(-0.03 \text{ C/m}^3\), which will have a significant effect on the dynamic behaviour under the DC electric field. Figure 15 shows the simulation results of the dynamic behaviours and electric field distribution under the DC electric field. Under the relative low DC electric field (E-field strength is below 0.4 kV/cm), the dynamic behaviours of the water droplet are mainly affected by the Coulomb's force. A large number of negative charges move along the opposite direction of the electric field, resulting in the deformation of the droplet.

When there is no water droplet, the initial average electric field strength in the calculation domain is 0.3 kV/mm. The first frame in Figure 15a shows the droplet at \( t = 0.0 \text{ s} \) when the electric field is applied, but the droplet has neither moved nor deformed. It can be seen that the maximum E-field distortion in the static state is 0.43 kV/mm. As shown in Figure 15b, the water droplet is deformed to the left, and the electric field distortion at the tip is more severe due to the accumulation of negative charge. The distortion of the electric field caused by the charged water droplet in the process of movement is up to 3.37 kV/mm, which is 11 times more than the initial average electric field strength (0. 3 kV/mm), as shown in Figure 15c.

Figure 16 shows the distribution of AC electric field in the process of water droplet movement. Similar to Figure 15a, the first frame in Figure 16a shows the droplet at \( t = 0.0 \text{ s} \) when the electric field is applied, as the droplet has neither moved nor deformed, the maximum E-field distortion in the static state is 0.42 kV/mm. The water droplet moves from left to right, and the E-field distortion goes up and down during one time period (0.02 s).

The experimental and simulation results of the maximum elongation factor \( L_n \) of the water droplet changing with
different volumes are compared in Figure 17. The influence of volume on the moving process of a droplet in simulation is consistent with our experimental results. The maximum value of the elongation factor increases with volume under both DC and AC, as shown in Figure 17.

Figure 18 shows the diagram of the relationship between the maximum electric field and the simulation time under DC and AC electric field. It is shown in Figure 18 that the elongation factor of water droplet has an increasing tendency as the applied E-field rises. The maximum E-field changes periodically with the left-to-right movement of the water droplets under the applied 50 Hz AC voltage, while the maximum E-field increases continuously under the applied DC voltage.

4.3 | Theoretical analysis of experimental and simulating results

First, in Section 3, it was proved that the motion modes of separate water droplet are different under AC and DC voltages, leading to the different deformation parameters (see Figure 17) caused by the motions. The shape change of water droplet,
especially in the elongation, on surface of silicone rubber under DC voltage is much larger than that under AC voltage. In addition, we found that the increase in the elongation factor leads to more serious electric field distortion, and the large volume of water droplets will induce E-field distortion.

Secondly, the maximum E-field (at the triple junction of the SIR surface, water droplet and air) under DC voltage is greater than that under AC according to our previous simulation in this manuscript (see Section 4). Therefore, it is easy to conclude that the maximum distorted electric field strength is greater in DC than AC (see Figure 18).

Thirdly, according to [23–25,29,30], the arc is always initiated at the position with the largest electric field, and the streamer inception can be described by Townsend mechanism. As the dynamic behaviours of the water droplet under DC electric field will cause more serious distortion of the electric field than that under AC. In addition, the accumulation of net negative charges will further increase the distortion of the electric field. Therefore, an easier initiation of local arc and a lower flashover voltage of the water droplet on the surface of SIR composite insulator could be found in DC than in AC.

5 | CONCLUSIONS

In the present work, we have investigated the dynamic behaviours of a single water droplet on the SIR insulating surface subjected to DC/AC electric field, using experimental and phase-field computational method. More importantly, the motion laws for the dynamic behaviours of water droplets under DC/AC were presented, and the mechanisms behind them were explained by the principles of physics. The results we got can be summarised as follows:

1. The causes of the difference between AC and DC flashover voltage are related to the dynamic behaviours of the water droplet.
2. Under DC electric field, the dynamic process of a water droplet can be attributed to force balance, which is the balance of Coulomb's force, Maxwell stress and surface tension. There are three main stages of water deformation and elongation. The deformation and elongation factors of the water droplet will be influenced by the 'Recovery' phenomenon under DC E-field.
3. Under AC electric field, the moving process and mechanism of a water droplet is different from DC in this article. With the increase in applied voltage, there will be various kinds of oscillations of the water droplet with different frequency. However, the left–right oscillation of the whole water droplet with power frequency will more obviously enhance the elongation of water droplet.
4. The dynamic behaviours of a water droplet, which depend on the applied E-field and the volume of the droplet, will induce the distortion of E-field. The different dynamic elongating behaviours and flashover performances for a single water droplet under DC/AC electric field are both affected by the volume of droplet.
5. In addition, we perform computer simulation by the finite element method to study the electric-field distributions and dynamic behaviours of a water droplet, and the findings are in good consistency with our experimental results, proving the rationality of our theoretical model.

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