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Deformation of water droplets on solid surface in electric field

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Abstract

The purpose of this paper is to analyze the deformation of water droplets on a solid surface under electric stress. A mathematical model making it possible to simulate the axisymmetric as well as non-axisymmetric deformations of droplets is developed. According to this model, the droplet deformation depends on several parameters such as the volume and the number of droplets, the conductivity and the permittivity of droplets, their proximity to one another, the surface of the solid material, and the location of each droplet on the dielectric surface. The results of the simulation show the disturbance of the background field through the presence of a single or multiple droplets. An experimental study is also achieved by considering one to three droplets aligned simultaneously on a dielectric smooth surface between two electrodes subjected to AC voltages. The influence of the background field and the droplet location regarding the electrodes on the deformation of water droplets are evidenced.

Keywords: Dielectric solid surface; Sessile droplet; Contact angle; Interfacial tension; Electric field strength; Weber number

1. Introduction

Composite insulators made from silicone are largely used in the transport lines, and electric power distribution over the world. One of the great advantages of this type of outdoor insulator is their exceptional performance under contaminated conditions [1]. In spite of these advantages, the criteria for the selection and design of polymeric insulators are still based on the leakage distances from those prescribed for ceramic insulators [2,3]. Such an approach of pessimistic design mainly results from the loss of hydrophobicity in service and the non-understanding of flashover mechanism of polluted polymeric insulators. Several works suggest that the key to the problem resides in the understanding of the flashover mechanism of non-ceramic insulators and particularly the influence of water droplets on this mechanism. Thus, the understanding of flashover of contaminated polymeric surfaces requires the knowledge of the influence of the electric field on water droplets. It is well known that polymers are water-repellent. They possess the property of preventing water droplets from wetting their surfaces. This is characterized by relatively large contact angles. These contact angles however can change when an electric field is applied. This initial deformation of droplets leads to the disruption along the polymeric surface accompanied by a glow or spark discharge most of the time.

Deformation of water droplets on dielectric surface under electric stress has been the subject of a certain number of experimental works [4,5]. These are mainly qualitative studies of the behavior of water droplets under AC voltage stress. It was observed that the droplet vibrations depend on the frequency of the applied voltage. The influence of droplet deformation on the DC corona discharge was also reported [6]. Higashiyama et al. [6] showed that during the droplet deformation corona discharge occurs at the droplet tips. Braunsberg et al. [7] studied the correlation between the levels of partial discharges (PD) and the state of the hydrophobicity of non-ceramic outdoor insulators.

A number of authors have conducted numerical studies of the deformation of drops on solid surface. Patankar and Chen [8] developed a numerical tool and studied the relationship between the roughness characteristics and the apparent contact angle and motion of liquid drops on rough surfaces. They used a modified public domain software to numerically

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investigate the three-dimensional equilibrium drop shapes on a rough surface. The effect of gravity on the drop shapes was unfortunately neglected. In the same way, Brandon et al. [9] simulated three-dimensional sessile drops in equilibrium with a model chemically heterogeneous smooth solid surface. Results are presented for a model system in which the intrinsic contact angle is assumed to vary along the surface in a periodic manner. So far, very few papers deal with numerical computations of deformation of water droplet on solid surface in an electric field. Schreiber and van Rienen [10] simulated the behavior of droplets on the surface of polymeric insulator under AC voltage stress using Maxwell's equations and the finite integration technique (FIT).

The fundamental issues associated with simulation of shapes of water droplet in an electric field have been addressed in a series of papers by Langemann and co-workers [11]. These authors propose numerical algorithms for two- and three-dimensional models of conductive water droplets. They regard the stationary droplet shapes for different electric field strengths, and they solve the feedback problems by considering the electric field around a given droplet. But, the dependence of the droplet deformation of a given droplet on the shapes of eventually nearby droplets has not been assumed in these models. Practically, more than one rainwater droplet deposed simultaneously on the insulator sheds and drop the dielectric strength of the insulator [12].

The purpose of this paper is to study the deformation of water droplets on a solid surface under electric stress which is the key phenomenon behind the flashover mechanism of non-ceramic insulators. A model enabling us to describe the deformation of a droplet as well as a mathematical approach to the considering of the field enhancement at droplet tips are presented. The model developed considers also the influence of the nearby droplets on the droplet subjected to deformation on a horizontal surface. An experimental analysis has been also made under AC voltage. We regard only horizontal surface position, because practically, the original tilted surface for the sheds of outdoor insulator can also become horizontal for rainwater droplets.

2. Droplet shape analysis

2.1. Description of the system

Let us consider a water droplet on a dielectric solid surface subjected to an electric field (Fig. 1). The solid surface is smooth, horizontal and does not dissolve or react with the used water. It is in contact with a water droplet with liquid/solid, gas/solid and gas/liquid interfaces that conjoin at a contact line. The angle between the liquid/solid interface and gas/liquid interface is the so-called contact angle. The gas around the droplet is a perfect dielectric steam with zero electric conductivity. Furthermore, there is no free charge around the droplet. We consider rainwater as conductive and incompressible [4]. The gas/liquid interface is characterized by an uniform surface tension, and the electric permittivity in each phase is uniform.

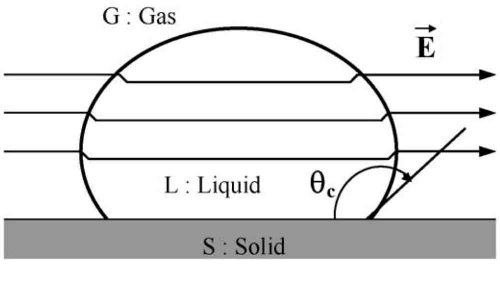

Fig. 1. Contact angle and interfaces in a gas/liquid/solid system.

When an electric field is applied to the sessile water droplet, its shape can change. It is considered that the changing of the shape or distortion of the droplet is characterized by the motion of

- the gas/liquid interface I_{GL} in the direction normal to the interface, and
- the contact line L_{GLS} parallel to the solid surface and normal to the contact.

In principle, the deformation of the droplet occurs in the direction of the electric field strength. This deformation is a result of the change of the different interface energies U, and the change of the negative work W supply to the gas/liquid interface and the contact line subjected to external actions. The variation of the Gibbs free energy G of both interface I_{GL} and contact line L_{GLS} can be expressed by the equation

$$\mathrm{d}G = \mathrm{d}U - \mathrm{d}W \tag{1}$$

with

$$\mathrm{d}U = \gamma_{\mathrm{GS}}\,\mathrm{d}A_{\mathrm{GS}} + \gamma_{\mathrm{LS}}\,\mathrm{d}A_{\mathrm{LS}} + \gamma_{\mathrm{GL}}\,\mathrm{d}A_{\mathrm{GL}}, \tag{2}$$

$$\mathrm{d}W = \sum f_I\,\mathrm{d}V_I, \tag{3}$$

where γ and A are respectively the interfacial tension and the area of the corresponding interface.

The indexes G, L and S refer to the surrounding gas, liquid and solid surface, respectively. In Eq. (3), $\sum f_I$ is the sum of the external forces per unit area corresponding to the external actions of the system.

Consider a small motion of I_{GL} and L_{GLS} that may not obey any kinetic law [13–15]. The line element of L_{GLS} sweeps a surface element $\mathrm{d}A_{\mathrm{L}}$ during the virtual motion of the contact line L_{GLS}. In the same way, the virtual motion of I_{GL} is characterized by the volume variation $\mathrm{d}V_I$. Thus, Eq. (2) can be expressed as

$$\mathrm{d}U = \big(\gamma_{\mathrm{GS}} - \gamma_{\mathrm{LS}} - \gamma_{\mathrm{GL}}\cos(\theta_{\mathrm{C}})\big)\,\mathrm{d}A_{\mathrm{L}} + \gamma_{\mathrm{GL}}(\vec{\nabla}\cdot\vec{n})\,\mathrm{d}V_I, \tag{4}$$

where $\vec{\nabla}\cdot\vec{n}$ is the mean curvature of I_{GL} and θ_{C} is the contact angle; $\vec{n}$ is a unit vector normal to I_{GL} and $\vec{\nabla}$ is the mathematical Nabla operator. Substitution of Eqs. (3) and (4) into Eq. (1) yields

$$\begin{aligned}\mathrm{d}G = {} & \big(\gamma_{\mathrm{GS}} - \gamma_{\mathrm{LS}} - \gamma_{\mathrm{GL}}\cos(\theta_{\mathrm{C}})\big)\,\mathrm{d}A_{\mathrm{L}} \\ & + \Big(\gamma_{\mathrm{GL}}(\vec{\nabla}\cdot\vec{n}) - \sum f_I\Big)\,\mathrm{d}V_I.\end{aligned} \tag{5}$$