Dynamics of a water/air interface on insulating solid surface submitted to DC high voltage

Jean Ndoumbe, Adolphe Moukengué Imano, Abderrahmane Beroual

DYNAMICS OF A WATER/AIR INTERFACE ON INSULATING SOLID SURFACE SUBMITTED TO DC HIGH VOLTAGE

J. Ndoumbe [1,2], A. Moukengue Imano [3] and A. Beroual [1]

[1]Ecole Centrale de Lyon, AMPERE Lab CNRS UMR 5005, 36 Avenue Guy de Collongue, 69134 Ecully, France
[2] Faculty of Industrial Engineering, University of Douala, BP 2701 Douala, Cameroon
[3] Faculty of Sciences, University of Douala, BP 24157 Douala, Cameroon

Email: jean.ndoumbe@ec-lyon.fr

Abstract: The interaction of electrical fields and liquids can lead to complex phenomenon such as spraying jets, Taylor cone and sideways wobbling. The focus of this paper is to investigate the dynamics of a water/air interface when water droplet or water puddle sitting on an insulating surface is submitted to DC voltage. Hence, under a uniform field loss of stability occurs through a subdivision of the water film on many small water puddles. However, under a non-uniform electric field destabilization may occur at a point at which the film profile already exhibits a finite-amplitude deformation. An experimental study of the deformation of a water droplet and water puddle on composite insulating surface in rod to plane electrodes configuration is undertaken. The critical electric field strength at which a water/air interface becomes unstable is determined. Variation of the free surface deformations relative to the applied voltage and typical current discharges characteristic from water/air interface are presented. The behaviour of the inception field strength of partial discharges between water/air interface and rod electrode also is shown. The results show that the electric field applied to the water/air interface is determined by the electrode geometry and the spacing between water surface and the electrode.

1   INTRODUCTION

Water droplets sitting on composite insulating surfaces in electric field exhibit much behaviour depending on the electric field strengths and the fluid properties. They can deform, elongate, disintegrate or coalesce. In case of coalescence, water droplets may form a film of water on insulator surface. The equilibrium shape of an interface separating a liquid film from an ambient fluid subjected to an electric field is flat so long as the field strength is below a critical value. It has been observed that the surface of water film or water puddle under high voltage stress becomes unstable from a certain value of the electric field and can lead to the occurrence of partial discharges. These partial discharges can change the hydrophobic properties of the composite insulating surface. With such changes, the whole insulation system can be destroying.

The dynamics of water droplets has been the subject of a certain number of experimental works. Benjamin and Ursell [1] investigate theoretically and experimentally the stability of the plane free surface of water. Roero and Teich [2] investigate experimentally also the behavior of droplets on different high voltage conductors showing high framing rate records of their periodic deformation in the electric field. Finally, Lord Rayleigh [3] analyzed the equilibrium conditions for a conducting liquid in vertical electric field. His approximate treatment allowed him to determine a stable equilibrium shape for a conducting liquid under a given applied electric field strength.

The aim of this paper is to investigate the dynamic of an electrified water droplet and water surface. Precisely, we use firstly a mathematical model to calculate the theoretical electric field strength at the water/air interface, and secondly we regard experimentally the discharges initiation and development between water/air interface and insulating surface on metal electrode. The results of the investigation can provide a better understanding of the approach used elsewhere [4] to compute the field inhomogeneity factor according to Schwaiger, and to determine the critical electric field strength at which the water/air interface becomes unstable using a virtual sphere according to Taylor.

2   WATER/AIR INTERFACE ANALYSIS

2.1   Description of the water/air interface

Consider a water droplet or a water film on an insulating solid substrate subject to DC non-

uniform electric field, as shown in Figure 1. When the electric pressure acts at the surface of the film, the water film can become unstable. In this case, the water film can lower its free energy by changing its thickness and becomes therefore unstable. The stability of liquid films on solid substrates has been widely studied both theoretically and experimentally [1, 4–9]. The process of instability formation can be modelled using two main approaches: an Electrohydrodynamic (EHD) approach and an energetic approach. In EHD approach, the motion of the fluid is described using the Navier-Stokes equations of fluid flow with the appropriate boundary conditions. In the energetic approach, the instability is a result of the change of the different interface energies, and the change of the negative work supplied to the water/air interface and the contact line subjected to external forces.
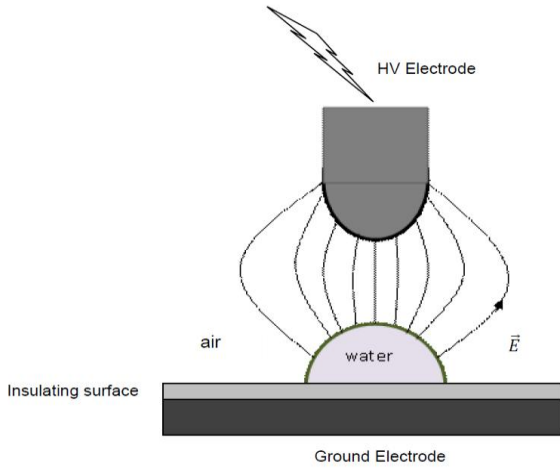

Figure1: Electrode arrangement with a water droplet submitted to electric field

In this study, the second approach is considered as in [4]. The water/air, water/electrode and air/electrode interfaces conjoin at a so-called contact line. For the gas around the droplet and the used water, the liquid is assumed to be incompressible with constant density, ρ, viscosity, μ, and surface tension, γ. The film is subjected to an electric field, of strength E_0; the air above it is assumed to be a perfect dielectric with constant permittivity ε_0. The electric potential above the film, ψ, satisfies the relation $E = -\nabla\psi$ where E is the electric field. The liquid is assumed to be a conductor so that there is no potential difference between the substrate and the free surface and, hence, no electric field within the film. The contact line is subjected to external forces due to the interfacial tension, the pressure difference, the electric stress, the effect of the viscosity and the gravity.

The reduction of the Gibbs free energy of both water/air interface and contact line towards zero, enables us to obtain the main equation of the shape of the water/air interface I_{WA} at the equilibrium state [5]

$$\gamma_{WA} \cdot (\overrightarrow{\nabla \cdot \vec{n}}) - \sum f_I = 0 \qquad (1)$$

Let us decompose the force balance given by equation (1) into normal and tangential components, according to Figure 2. The interaction of all external and internal forces in the direction normal to I_{WA} enables us to rewrite equation (1) in

$$\vec{n} \cdot \sum f_I = \vec{F}_p + \vec{F}_{En} + \vec{F}_{\mu n} + \vec{F}_g = \vec{F}_\gamma \qquad (2)$$

with

$$\vec{F}_p = -\vec{n} \cdot \Delta p \qquad (3)$$

$$\vec{F}_{En} = \vec{n} \cdot T_n \qquad (4)$$

$$\vec{F}_{\mu n} = \vec{n} \cdot 2\mu\vartheta_n(\overrightarrow{\nabla \cdot \vec{n}}) \qquad (5)$$

$$\vec{F}_g = \vec{n} \cdot g \cdot \Delta\rho \cdot z \qquad (6)$$

$$\vec{F}_\gamma = \vec{n} \cdot \gamma_{WA}(\overrightarrow{\nabla \cdot \vec{n}}) \qquad (7)$$

Contrary to the simplifications made elsewhere [4], the consideration of viscosity makes it possible to take into account the force interaction in the direction tangential to I_{WA}. According to G.I. Taylor [10], only the tangential components of the forces due to the electric stress and to the effect of the viscosity interact in the direction tangential to I_{WA} of the droplet, thus equation (2) becomes

$$\vec{F}_{Et} + \vec{F}_{\mu t} = \vec{0} \qquad (8)$$

with

$$\vec{F}_{Et} = \vec{t} \cdot T_t \qquad (9)$$

$$\vec{F}_{\mu t} = \vec{t} \cdot 2\mu\vartheta_n(\overrightarrow{\nabla \cdot \vec{n}}) \qquad (10)$$
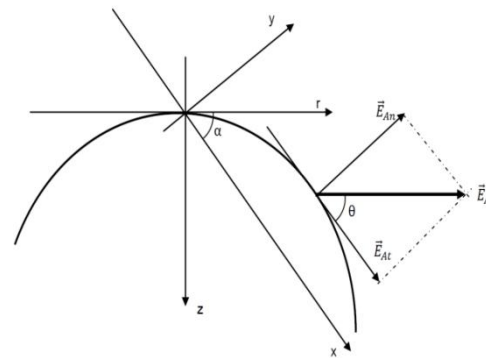

Figure 2: Normal and tangential components of the electric field at the water/air interface

2.2 Equation of the shape of the water/air interface

For generalization of computation results, the system of the differential equations of the shape of I_{WA} can be written in a non-dimensional form as [5]

$$\frac{d\theta}{dS} = \frac{1}{\left(1-T_0\frac{\sqrt{X^2-Y^2}}{t}\cos\theta\right)}[1 + B_0 \cdot Z +$$

$$W_{e0} \cdot \cos^2\alpha \cdot (K_1 + K_2 \cdot \cos^2\theta)]$$

$$- \frac{\sin\theta + (\Omega_{e0}\cdot\delta\cdot t\cdot\cos^2\alpha\cdot\cos\theta)}{\sqrt{X^2-Y^2}} \qquad (11)$$

$$\frac{dX}{dS} = \cos\theta \cdot \cos\alpha \qquad (12)$$

$$\frac{dY}{dS} = \cos\theta \cdot \sin\alpha \qquad (13)$$

$$\frac{dZ}{dS} = \sin\theta \qquad (14)$$

with $S = b \cdot s$, $Y = y \cdot s$ and $Z = b \cdot z$, where

- $b = \frac{1}{R_{Apex}}$ is the curvature at the origin of the coordinates (Apex);
- $T_0 = 13.76 \cdot R_i$ is the time constant in s;
- $\Omega_{e0} = 44.21 \cdot E_{G\infty}^2$ is an electric parameter in S^{-1} for homogeneous electric field and for unit area;
- $B_0 = 67.23 \cdot 10^{-3} \cdot R_i^2$ is the non-dimensional Bond number;
- $W_{e0} = 3.08 \cdot 10^{-4} \cdot E_{G\infty}^2 \cdot R_i$ is the electric non-dimensional Weber number for homogeneous electric field and for unit area;
- $\delta = E_n^2$ is a non-dimensional form factor for electric field;
- $E_{G\infty}$ is the electric field strength of a homogeneous electric field in kV/cm, for a water temperature of 20° C;
- R_i is the initial radius of the droplet in mm;
- $K_1 = 1$ and $K_2 = 78.18$ are non-dimensional electric constants;

2.3 Calculation of the form factor of the electric field at water/air interface

For a sessile droplet on an insulating solid surface, the deformed water/air interface enhances the initial electric field at its tip. This positive feedback phenomenon can cause further distortion of the droplet. Furthermore and under certain conditions, the sessile water droplet can disintegrate or jump to the faced electrode. Consider *E* as the electric field strength of the normal component of an electric field at one of the elementary points on the droplet tip (Figure 3). For a sessile droplet, this electric field strength can be given by

$$E = \frac{U}{\eta(d-h)} = \frac{U}{d} \cdot \frac{1}{\eta\left(1-\frac{h}{d}\right)} \qquad (15)$$

η , h, U and d are respectively a corresponding inhomogeneity factor for the droplet-electrode configuration, the height of the droplet (or water film), a potential difference and the shortest distance between both electrodes. It is assumed that the water considered is conductive.

Without water droplet, this electric field strength can be expressed as

$$E_0 = \frac{U}{\eta_0 d} \qquad (16)$$

η_0 *is* a corresponding inhomogeneity factor for the electrode-electrode configuration. One defines in this case the electric form factor, as

$$E_n = \frac{1}{\eta\left(1-\frac{h}{d}\right)} \qquad (17)$$

for droplet configuration, and also

$$E_{n0} = \frac{1}{\eta_0} \qquad (18)$$

for electrode-electrode configuration without the sessile droplet.

To determinate E_n for the water surface and electrode configuration, it was assumed that the deformation of the water surface have only a neglected influence on the distance between electrode und water surface.

In our case, the inhomogeneity factor according to Schwaiger [11] can be approximated to

$$\eta = a^{-0.904} \qquad (19)$$

for droplet faced to rod electrode, with *a* the spacing between the droplet tip and the opposed rod electrode in mm.
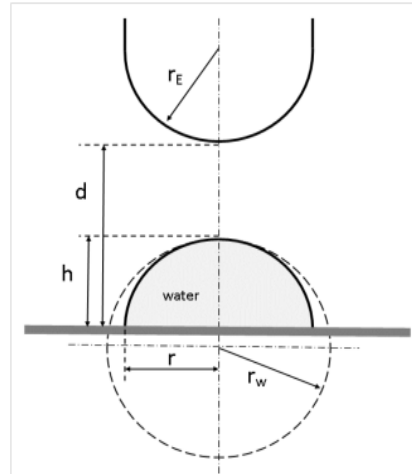

Figure 3: Top view of the droplet faced to rod electrode.

3   EXPERIMENTAL STUDY

To study the dynamic of the water/air interface, we have conducted experiments with sessile water droplet on insulating surface submitted to DC high voltage.

3.1 Experimental setup

Figure 4 shows the completed experimental setup with an electrodes arrangement. The rod electrode is connected to DC high voltage source and the plate electrode connected to ground. For water droplet and generally water surface, we used tap water with a conductivity of 300 µS/cm. The volume of the droplet was 80 µl. This sessile droplet was deposited on the insulating surface which is placed on plane electrode with the help of a micro-pipette, as shown in Figure 5 for rod-plane electrode arrangement.

The applied DC voltage on the electrodes arrangement and the potential drop across the resistance R_m (75 Ω, 1/4 W) fed directly to a high time resolution oscilloscope (1 GHz, 4 Gsa/s) to measure the discharge current characteristics. The behaviour of the drop surface was recorded by using a high resolution CCD camera (767x580 pixels) with rate of 50 frames per second connected to the PC through a high performance video card.

The DC voltage was increased gradually until the first partial discharges (PD) occurred. The exact value of the PD inception voltage and the voltage shape were recorded with a digital storage oscilloscope.
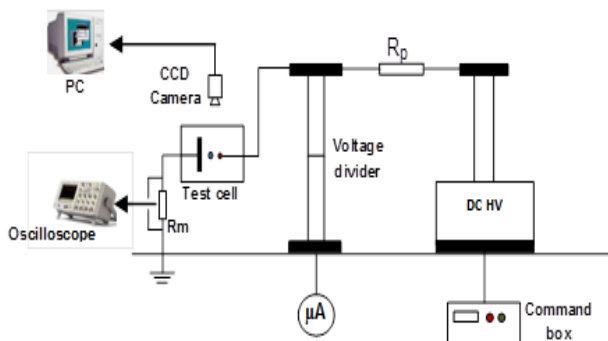

Figure 4: Schematic diagram of the experimental set-up.

4 RESULTS

4.1 The partial discharges initiation

The initiation voltage of the partial discharges (PD) between a droplet surface and metal electrode ones depend on the initial geometry and a further deformation of the droplet. Figure 5 shows the behaviour of the PD inception field strength of the droplet surface faced to the rod electrode, with respect to spacing.

The experimentally determined field strength gives the critical condition for the stability of the water/air interface, and is observed for spacing up to 7.5 mm. It can also be observed, that for relative small gap distances the water/air interface surface becomes quickly unstable.

4.2 The instability of the water/air interface

A potential U of up to 14 kV could be applied to the water drop by means of continuously variable power supply. Higher values of potential tended to cause the water/air interface to become unstable or a water droplet to move up from the insulating surface to rod electrode. The behaviour of the recorded current illustrates clearly the dynamic of water/air interface. All recorded results show that when the applied voltage reached a certain value, a current begin to flow between the metal electrode and the droplet or water surface. Figure 6 shows typical discharges development for a sessile drop placed at a distance of 4.10 mm to the rod electrode.
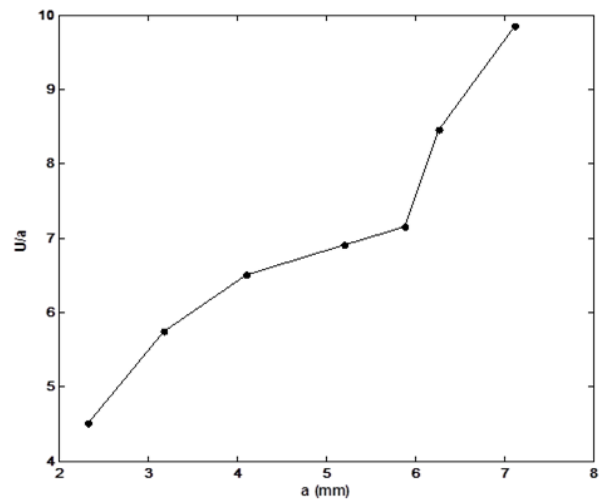

Figure 5: Relative PD inception field strength of a sessile droplet versus spacing (*a*) for rod electrode.
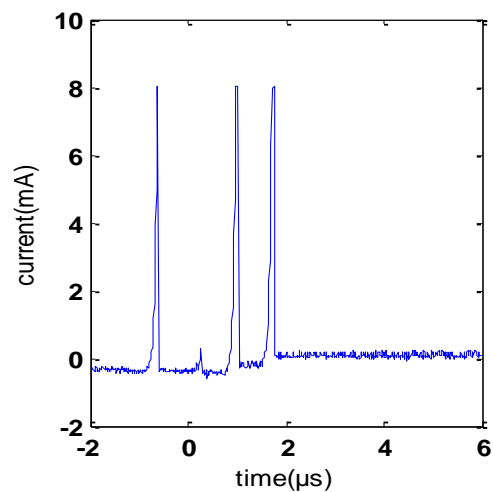

Figure 6: Typical current measured during a discharge development for a water/air interface at spacing of 4.10 mm to the rod electrode.

5   CONCLUSION

The dynamic of the water droplet sitting on an insulating solid surface is hereby evidenced through the flow of impulse current in the gap do to corona discharges at the water/air interface. Furthermore as expected, the obtained results enable us also to affirm, that the electric field applied to the water/air interface is controlled by the electrode geometry and spacing between water surface and the electrode.

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