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CHARGING AND DEFORMATION OF WATER DROPLETS ON COMPOSITE INSULATING SURFACE STRESSED BY DC ELECTRIC HIGH VOLTAGE

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Abstract: This paper deals with experimental investigations of the charging and the deformation of water droplets sitting on composite insulating (silicon rubber) surface under non-uniform DC high voltage electric field. Accordingly, the effects of electrodes geometry, droplets size and water droplet conductivity are analyzed. The amount of charge on water droplet surface was estimated through the measurement of current flowing in the circuit. Increasing the electric field strength, the charges accumulates on the droplet surface also increases. The results obtained show that the charges acquired by droplet increases with droplet size. It also shown that electrode geometry have a significantly effect on the amount of charges on droplet surface.

1. INTRODUCTION

Composite insulators are now dominant at overhead transmission lines particularly in outdoor insulation system. Their proper and continuous function is important to power system reliability. However they generally encounter problems that are associated to discharge activity resulting from local electric stress enhancement on the surface of device. The electric stress enhancement may be induced by environmental elements. In service, environmental stress as rain, snow, condensation, frozen leads to formation of water droplets on the insulator surfaces. When subjected to an external electric field, the water droplets get polarized and their presence distorts in turn the electric field. Also, the accumulation of electric charges resulting of different phenomena (injection, pollution …), at the surface of water droplets may cause their deformation/elongation that can reduce/shorten the insulating distance leading generally to insulator flashover. Water droplet dynamics and charging has been of interest of many researchers. Theoretical and experimental investigations were conducted. [1-6]. The behaviour of electrified liquid and charged droplets in an electric field was first reported by Zeleny [1]. He studied the role of the surface instability in electrical discharges from charged droplets. In the 1960s, Taylor [2] explained the conical formation phenomenon emitting thin jet and the eventual break-up of the jet into micro charged droplets. He identified the critical electrical potential for an electrostatic formation of a cone of liquid (now known as a Taylor cone). Lord Raleigh [3] studied the instabilities that occur in electrically charged liquid droplets. He calculated the maximum amount of charge that a drop of liquid can maintain before the electrical forces overcame the surface tension of the drop and lead to the creation of a jet.

Recently, Shrimpton [4] has proposed an extension to Rayleigh's theory. He takes account in his study the dielectric nature of charged droplets. He suggests that dielectric droplets contain an internal electric field that causes polarization and aligns the molecules within charged droplets according to the applied electric field. The polarization is purported to induce a charge on the droplet surface which increases the total charge on one side and reduces it on the other such that one side of the droplet is always unstable relative to the other and found that droplet can break-up at sub-Rayleigh limit. Hinde [5] studied water droplet discharges on the surface of high voltage composite insulators. He made the estimation of total charge for a large droplet by using a triangular approximation of the current pulse. Moukengue and Beroual [6] studied discharges from water drops on both conducting and dielectric solid surface in AC electric field. To the best of our knowledge, many points concerning the estimation of the electric charge accumulated to the surface of a droplet remain poorly understood particularly case of droplet sitting on hydrophobic surface. The present study is devoted to this problem when the surface was stressed by DC electric field.

2. THEORY OF DROPLET CHARGING

Electric field can induces charges into dielectric and electrically insulating droplet and then produces surface charge density. These induced charges are due to the difference in electrical properties within the droplet and the fluid where it immersed such as electrical conductivity. To highlight the charging phenomenon and dynamics of a water droplet assumed as conductive and incompressible particle which surrounded by vacuum also assume incompressible and dielectric medium, we considered that two mains forces acts on the droplet. The deformative/disintegrative electrostatic force and the surface tension force that hold the droplet within a spherical shape. Deformations for spherical shape increase the surface area of the droplet, thereby increasing its surface energy, but at the same time decrease the electrostatic repulsion by spreading the charge out [2]. At the equilibrium state, the two forces are balanced each other. This steady state can be expressed by:

$$\frac{Q^2}{4\pi\epsilon_0 D^2} = 2\pi\gamma D \qquad (1)$$

Where Q is the electrostatic charge on the surface of the droplet, $\epsilon_0$is the dielectric permittivity of the vacuum, γ the surface tension of the liquid and D the droplet diameter.

Increasing the electric field strength, the charges accumulates on the droplet surface also increases until reaches a critical point when the electrostatic force overcomes the surface tension. This critical point is the well known Rayleigh limit Q_R.

Some researchers [7.8] reported that instabilities of the charged can occurred at a sub-Rayleigh limit condition. So that the instability condition can be redefined as:

$$q = k\pi\sqrt{8\epsilon_0\gamma D^3} \qquad (2)$$

With k a Rayleigh limit coefficient ($k \leq 1$) this coefficient can take in account several parameters as the fact that the droplet is not spherical as it is sitting on the solid substrate.

For the charging process of droplets, other analytical models were proposed. According to Felici [6], and Vellunga and Klinkengerg [7], the droplet charge depends on the time of charge. The charge accumulates on the droplet surface can be expressed as function of time (t) by:

$$q = q_0 \exp\left(-{}^{t}/_{\tau}\right) \qquad (3)$$

Where τ is the relaxation time of droplet defined as

$$\tau = \frac{\epsilon_0\epsilon_r}{\sigma} \qquad (4)$$

With q_0 the charge acquired by the droplet at $t = 0$, $\square_0$ is the relative permittivity of the water droplet and σ is the conductivity of the water.

Felici have shown that a spherical particle in contact with an electrode can acquired electrical charge given by:

$$q_0 = 1.64\pi\epsilon_0 E_0 D^2 \qquad (5)$$

Where E_0 is the applied electric strength and D the diameter of the droplet. It assumes that no corona discharge occurred from the droplet.

3. EXPERIMENTAL SETUP

A schematic diagram of the experimental system used to monitoring the droplet dynamics in an electric field is shown on Figure 1. It consists of a DC high voltage power supply (0-200 kV), a test cell containing the electrode arrangement and the visualisation and measurement system.

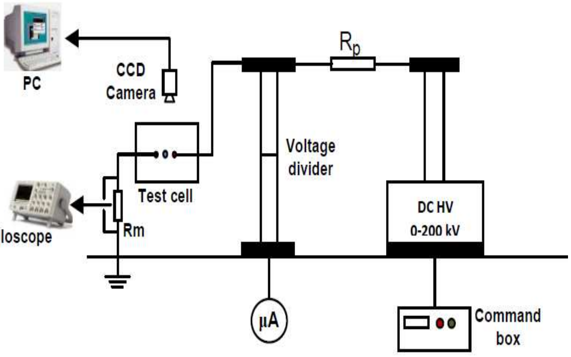

Figure 1: Schematic diagram of the experimental set-up

The dynamics of droplets on the insulator surface were captured by using a high resolution CCD camera (767x580 pixels) with rate of 50 frames per second connected to a PC through a high performance video card.

To obtain the charge transfer during the charging process, charge currents are measured with a high time resolution oscilloscope (1 GHz, 4 Gsa/s) via a resistor R_m (75 Ω, ¼ W) connected in series with the test cell. The charge transfer has been estimated for different inter-electrodes distances for distilled and tap water the conductivity of which are 0.5 μS/cm and 300 μS/cm, respectively. The electrical charge is obtained through the integration of the current. Two electrodes arrangement have been used: rod to plane electrode system (Figure 2a) and coplanar inclined cylindrical electrodes (Figure 2b). Both electrode arrangements provided non-uniform electric field.

Silicone sample of 96x96x3.5 mm was used for the coplanar inclined system and a circular one of 48 mm of radius was used for the rod to plane electrode system. Water droplet of knowing volume was deposited on the silicone sample surface using micro-pipette.

Figure 2a: Rod to plane electrode configuration with a circular silicon sample.

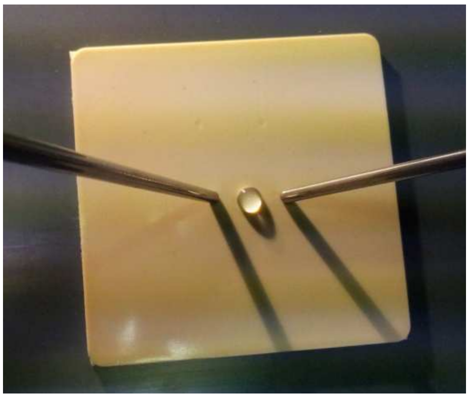

Figure 2b: Coplanar inclined cylindrical electrode configuration.

4. RESULTS

In order to investigate the dynamics behaviour of water droplets in electric field, the charge accumulated to the droplet was derived from the measurement of the electric current using numerical integration.

Figure 3 shows the calculated values of charge for varying droplet with different volumes and for varying the inter-electrodes distance. The total charge on the surface of the droplet was estimated by numerical approximation through Matlab software. When the applied voltage is lower than a critical value, there is no current detected by the oscilloscope. Figures 4a and 4b show typical current and associated charge for a droplet of 30 µl sitting on the silicone substrate and electrode gap of 11 mm. The current generally consists of a finite number of peaks of different magnitude. The associated charge is automatically obtained by the integral mathematic function of the oscilloscope. Figure 4b shows the enlargement of the first pulse of the current displayed by Figure 4a.

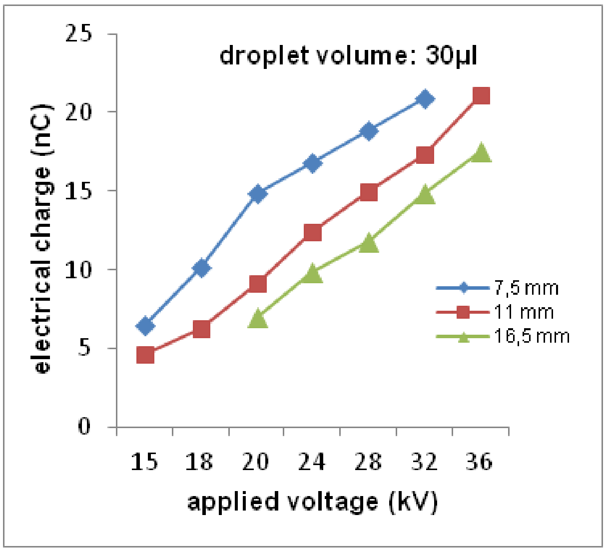

Figure 3: effect of applied voltage on the estimated electrical charge for various inter-electrode distances in rod to plane system.

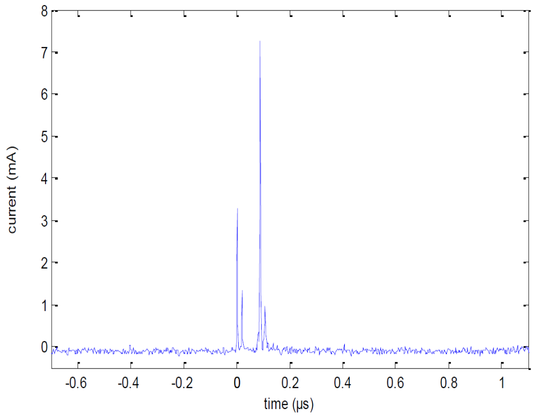

Figure 4a: Typical current detected for 30µl volume droplet at 28 kV for 11mm inter-electrode distance in rod to plane system.

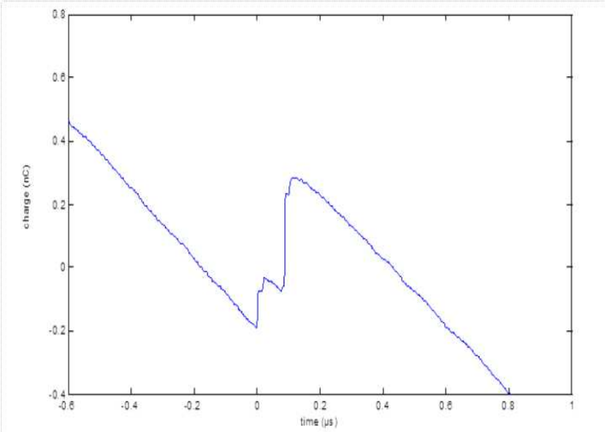

Figure 4b: Charge associated to the current displayed in Figure 3a.

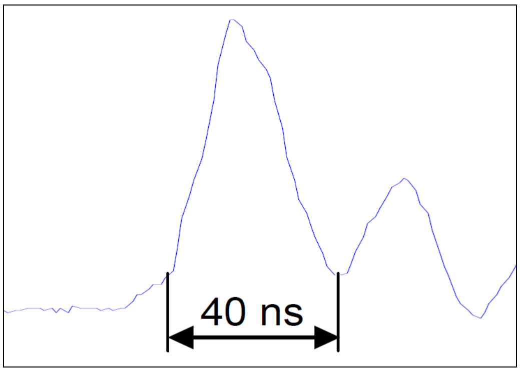

Figure 4c: Zoom of the first pulse of the current displayed in Figure 4a.

As mentioned above, two kinds of electrode arrangements are used in this experiment. The effect of water droplet volume on the estimated electrical charge on the droplet is shown in Figure 5. The charge acquired by droplet is too different on both electrode systems. For coplanar electrode arrangement, the deformation of the droplet limits the estimation of the electrical charge for small size droplets. For rod to plane configuration, the water droplet deformation was not found to be continuous with the increase of voltage as in the coplanar electrode system. The effect of the conductivity on the electric charge transfer to the droplet is shown on Figure 6. The experiments show that the charge acquired by the droplet increased significantly with the increase of the conductivity.

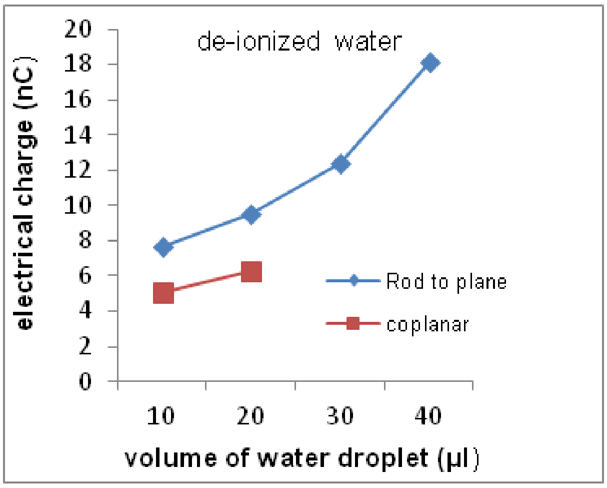

Figure 5: Variation of electrical charge on droplet surface with volume of droplet for both used electrode arrangements at 24 kV.

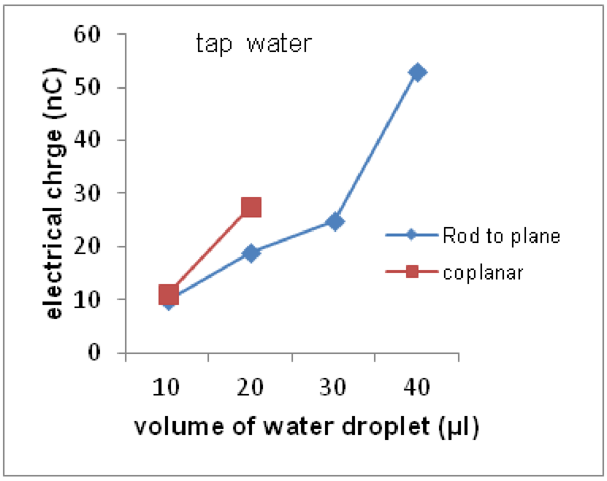

Figure 6: Effect of conductivity on the variation of electrical charge on droplet surface with volume of droplet for both used electrode arrangements at 24 kV.

5. CONCLUSION

Water droplet dynamics in non-uniform electric field was investigated to estimate the electrical charge on the surface of a droplet sitting on composite insulating sample. The experimental results show that the inter-electrode distance and the type of the electrode arrangement have a significant effect on the charge acquired by the droplet. The charge increases with the droplet volume and with the decrease of the inter-electrodes distance. It is also shows that the charge transfer to the droplet increased with the conductivity. It was found difficult to estimate the electrical charge acquired by the droplet in case of the planar electrode configuration due to high deformation of the droplet which leads to the flashover.

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