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COMMUNICATIONS

A STUDY OF THE BEHAVIOUR OF WATER DROPLETS UNDER THE INFLUENCE OF UNIFORM ELECTRIC FIELD IN EPOXY RESIN SAMPLES

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Water droplets on the surface of epoxy resin samples were investigated under the influence of uniform electric fields. Several parameters of water droplets were investigated *wrt* the flashover voltage of the epoxy resin samples, such as water conductivity, droplet volume, number of droplets as well as the positioning of the droplets regarding the electrodes. The droplet behavior is affected by the above mentioned parameters. Perhaps the most striking conclusion is that the flashover voltage depends more on the positioning of the droplets *wrt* the electrodes than on the droplet volume and/or number of droplets.

K e y w o r d s: partial discharges, epoxy resin, water droplets, polymeric surfaces

1 INTRODUCTION

Epoxy resin is widely used in many high voltage applications [1]. Epoxy resin is used in dry type transformers, indoor insulators and current transformers. Epoxy resin is also used as an important insulating component for machine insulation. It is a reliable insulating material resulting from addition polymerization, which is the combination of different types of monomer without splitting off side products [2]. Such a material suffers depending on the application from various deterioration phenomena, such as partial discharges [3], sudden impulses [4], surface effects and flashover voltages. The latter phenomena may appear in indoor applications [5] and they are of utmost importance for the better understanding of epoxy resin. In the context of this paper, an effort was made to study the effects of water droplets on the surface of epoxy resin samples under the influence of uniform electric fields. Water droplets under uniform electric fields present a particular research field because of their importance for the dry zones as well as for the resulting flashover. Parameters of interest are the water conductivity, the droplet volume, the number of droplets on the surface and the positioning of the droplets *wrt* the electrodes.

2 INTERFACES BETWEEN WATER DROPLET AND POLYMER SURFACE

In Fig. 1 the forces acting on the droplet are shown in case no applied field exists. Such forces are the surface tension of the liquid (τ_L), the surface tension of the solid (τ_S) and the interfacial tension between the droplet and the solid (δ_{SL}) [6]. An applied electric field results in a deformation/elongation of the water droplet. The tangential electric field on the surface of the polymer surface causes a force on the surface of the droplet, which in turn results in the deformation. This deformation influences the distribution of the electric field. Consequently, local field intensifications may result and subsequently micro-discharges between the droplets. Such a mechanism is the basis of the formation of dry zones and the root of the electro-chemical deterioration of the insulator surface [5, 6].

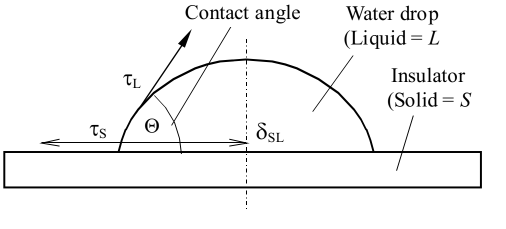

Fig. 1. Force balance at the interface between solid and liquid (after [6])

3 EXPERIMENTAL ARRANGEMENT

The voltage was supplied from a 20 kV transformer. The electrode arrangement with a sample is shown in Fig. 2. The dimension details of the electrodes are shown in Fig. 3. The electrodes were made of copper and they are half cylindrical with rounded edges. The electrodes were positioned on the epoxy resin sample at a distance of 2.5 cm from each other. The purpose of the experiments

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Fig. 2. Test arrangement for the experiments

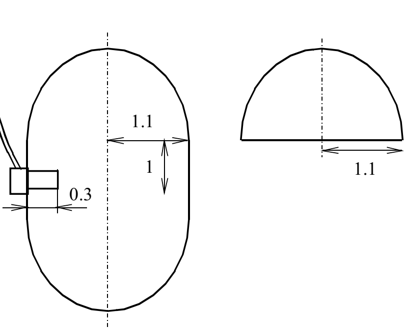

Fig. 3. Top view of one of the electrodes and cross-section (all dimensions in cm)

was to measure the flashover voltage with the different droplet arrangements at different conductivities. Attention was paid so that their surfaces were smooth with no asperities whatsoever. That was important for obtaining uniform electric fields.

The water droplets were accurately positioned on the epoxy resin surface with the aid of a special arrangement consisting of a metallic frame and three rules, one of which had two laser indicators. The water droplets were put on the surface with an appropriate syringe. The droplets arrangements are shown in Fig. 4. All dimensions in Fig. 4 are given in cm. The conductivities investigated were 1.3 μS/cm, 100 μS/cm, 200 μS/cm, 500 μS/cm, 1000 μS/cm, 2000 μS/cm and 5000 μS/cm. The measurements of the various conductivities were made with the aid of an electronic measuring device of conductivity of type WTW inoLab cond Level 1.

The following droplet arrangements were used: 1) one droplet of 0.05 ml volume each, 2) two droplets of 0.05 ml volume, with a distance of 0.8 cm between their centres, 3) three droplets of 0.05 ml volume each, forming a triangle, 4) four droplets of 0.05 ml each, 5) one droplet of 0.1 ml volume at a distance of 1.25 cm from the electrodes and 6) two droplets of 0.1 ml each at a distance of 1 cm from each other and 1.25 cm from the electrodes. Some of the droplet arrangements used are given in Fig. 5.

After putting the droplets on the epoxy resin surface, the voltage was slowly raised until flashover occurred. After that and after cleaning the surface and putting new droplets on it, the voltage was raised up to the previous breakdown value minus 1.2 kV, so that no new flashover would occur. At this voltage value, the arrangement could stay for 5 min. If no flashover occurred, the voltage was raised by 0.4 kV and the procedure is repeated until flashover occurred. The new flashover value was recorded. The reason for allowing the voltage for 5 min at each

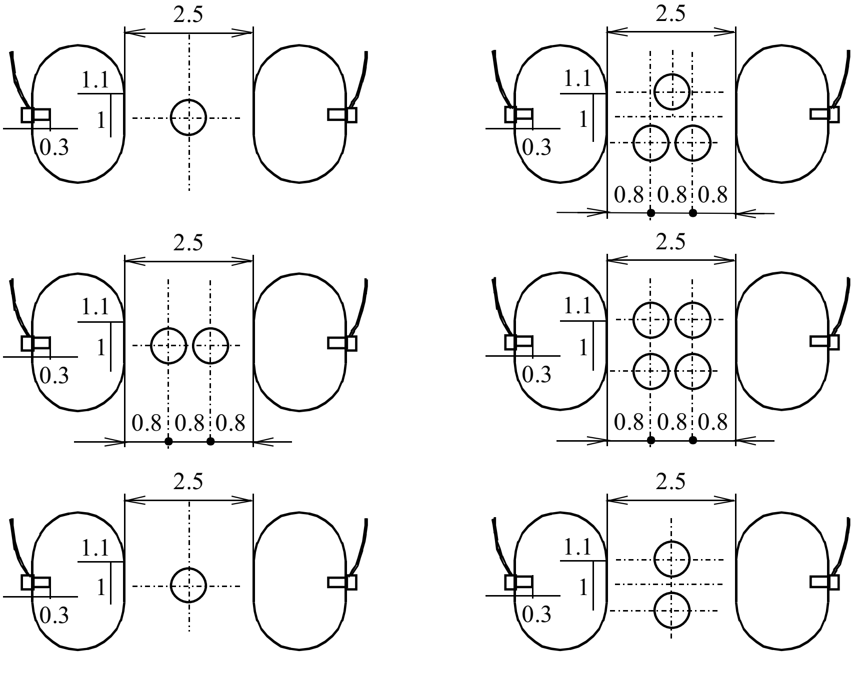

Fig. 4. Droplet arrangements for the experiments (all dimensions are given in cm)

Fig. 5. Various droplet arrangements

voltage value was because we wanted to give the necessary time for the droplets to deform and for the partial discharges to start.

4 EXPERIMENTAL RESULTS

During the tests with more droplets, there was a path uniting the electrodes. Such a path was not observed with one droplet. From the experiments it is evident that more droplet volume causes a lower flashover voltage. A larger droplet volume may mean a shorter distance of the droplets themselves from the electrodes. The number of droplets plays also an important role. However, a comparison between the droplet arrangements with two droplets (with volumes of 0.05 ml and 0.1 ml) indicates clearly the importance of the positioning of the droplets *wrt* the electrodes. Despite the fact that the two droplets of 0.1 ml each have a higher volume than the two droplets of 0.05 ml each, the former give a higher flashover voltage than the latter. This means that the droplet arrangement and the positioning from the electrodes are significant. For the experiments with more droplets, the damage of the epoxy samples was more pronounced than with fewer droplets. The results of the experiments are shown in Fig. 6.

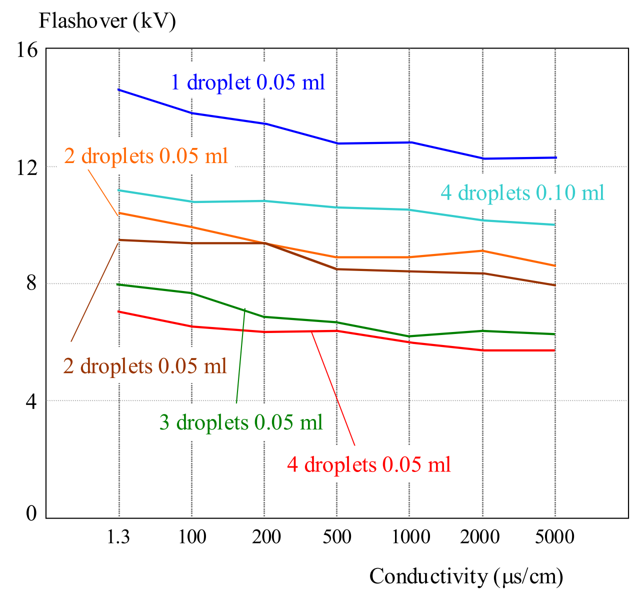

Fig. 6. Results from the experiments

5 DISCUSSION

From the results it is evident that an increase in droplet volume leads to a reduction of the flashover voltage [2]. An increase in water conductivity results in a reduction of the flashover voltage [1, 2]. This is clearly shown in Fig. 6. The larger number of droplets leads to a lower flashover voltage. When the applied voltage increases, the droplet starts oscillating and then it breaks up to smaller droplets [7, 8]. The positioning of the droplets *wrt* the electrodes plays a vital role, a more vital role than their volume. This can be explained by the fact that near the electrodes ionizing phenomena are easier to obtain, so with easier ionization the flashover voltage becomes lower. The latter is reminiscent of the relative easiness with which partial discharges take place in solid dielectric cavity, when one side of the enclosed cavity touches one of the electrodes [9].

As the voltage increases, the water droplet starts oscillating. This is because of the electric field exerted on the droplet. At a certain field value, the droplet breaks up to smaller droplets, ejecting them – sometimes – violently. When the droplet starts oscillating, it is likely that this will lead to a flashover after some time (at this or at a higher voltage). Remembering the theory developed by Felici on air bubbles in insulting liquids [10], and transferring some of the notions of [10] to our problem here, we may say that there can be four possible sequences of droplet behaviour: 1) elongation of the droplet, ignition (*ie* appearance of partial discharges), instability and break up, 2) no elongation of the droplet, ignition, instability and break up, 3) no elongation, ignition and no instability and 4) elongation but no ignition. In our experiments sequences 1) and 2) were observed but the sequences 3) and 4) were not observed. It is generally observed that droplets on polymeric surfaces elongate, ignite, then they become unstable and finally break up to smaller droplets. Because of the applied electric field, high field concentrations may develop, which in turn cause the droplet to break up.

Fig. 7. Damaged sample of epoxy resin

A criticism may be leveled against the present work regarding the high conductivities used for testing (especially those of 2000 μS/cmand 5000 μS/cm). The answer to this is that there is intense interest as to what happens in higher water conductivities (in case of heavy pollution) and that such high conductivities (and for that matter much higher, up to 22000 μS/cm) were already investigated in [11].

Surface discharges and flashover cause degradation of the epoxy resin. Such degradation was observed in the course of the experiments and is shown in Fig. 7. The degradation manifests itself as blackening spots and/or blackening areas. The conducting paths were created from one electrode to the other. The droplet (or droplets) start oscillating under the influence of the electric field and at a certain voltage a current flows through it. Such a current will evaporate part of the droplet causing it to elongate and/or to bridge the gap between the electrodes. The final flashover ensues either through the conducting path or through the air. The observed tracking is the visible effect of overstressing and of material decomposition [2], carbonization and volatilization of the epoxy resin [12]. Needless to say that such blackening of the epoxy resin was observed because of the rather high conductivities used.

On the other hand, such measurements, as those presented here, may be used as a guideline for a more detailed study of the early stage of aging in insulators. Especially with conductivities of up to about 200 μS/cm, one may follow the events of the early stage developments. Early stage aging may give valuable information as to the state of an insulation and appropriate measures can be taken. In our work here, conductivities of up to 200 μS/cm lead to minute spots on the surface of the epoxy resin sample. Early stage aging was elaborated previously in [13–15], and is characterized by discharges between droplets and the electrodes as well as between the droplets themselves. Early stage aging detection may be vital for diagnostic purposes since it may give information on the overall state of the insulation [5, 16]. Early stage of aging takes usually rather long time, it can be detected and appropriate measures can be taken in order to avoid complete flashover. The late stage of aging is short compared to the early stage of aging. In the late stage of aging the probability of a sudden flashover is high [17].

A further comment should be made regarding the results of flashover: as stated above, the droplets at a certain voltage start oscillating. The voltage recorded in all our experiments is the flashover voltage. The flashover may follow at the same voltage value or it may follow at a little higher voltage. In any case, there was not a big difference between the voltage value at which the droplets started oscillating and the final flashover voltage. For the experiments reported here, the difference between the two voltage values was not larger than 10%–15%. It has to be repeated again: in all experiments of this paper the flashover voltage was recorded and not the voltage at which the droplets start oscillating.

The behavior of a droplet on a polymer surface between two electrodes under a uniform electric field, was modeled in [18], where the electric field E_N developed at one edge of the droplet is given by

$$E_N = \frac{Uh}{a(h-a)} \tag{1}$$

where U is the applied voltage, a is the droplet radius and h is the distance of the center of the droplet from one of the electrodes. The electric field E_M on the opposite edge of the droplet is given by

$$E_M = \frac{U(L-h)}{a(L-h-a)} \tag{2}$$

where L is the distance between the electrodes, and the other symbols as in Eq. (1). With one droplet positioned in just the middle of the electrodes, the ratio E_N/E_M is expected to be unity, and this was what was exactly obtained with the above equations. In Eq. (1), if we consider that $h \to a$, then $E_N \to \infty$. In other words, the closer a droplet is in one of the electrodes, the larger is the electric field [19].

6 CONCLUSIONS

In this paper, water droplets positioned on epoxy resin samples were investigated under the influence of uniform electric fields. Droplet positioning *wrt* the electrodes plays a dominant role in determining the flashover voltage. Other parameters affecting the flashover voltage are also water conductivity, number of droplets and droplet volume.

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