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Water Droplets on Polymeric Surfaces under the Influence of High Voltages

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In this paper, the problems arising from the application of uniform AC electric fields on water droplets, which are on polymer surfaces, are investigated. Polymeric materials such as silicone rubber, PVC and rubber were used. The flashover voltage was investigated in terms of water conductivity, polymer surface roughness, droplet volume and droplet position w.r.t. the electrodes. Our research showed that all four aforementioned parameters influence the flashover voltage.

***Key words**: Water droplets, micro-discharges, arcs, polymeric materials, surface pollution*

1.0 INTRODUCTION

Water droplets on polymeric surfaces may cause—under the influence of an applied electrical field—deterioration, even in conditions of low pollution. This is due to the fact that water droplets locally increase the applied field. Local field intensification leads to partial discharges (PD) and/or localised arcs which in turn render possible the creation of dry bands and subsequently to a complete flashover. This mechanism is valid—to a greater or lesser extent—for both outdoor and indoor insulation although each of the aforementioned categories has its own special characteristics, i.e. indoor insulation is stressed more and is subjected to different types of environmental influences [1, 2]. A combination of water droplets and dust-like impurities may lead to a conducting contamination layer which may in turn lead to a reduction of flashover voltage. It is clear from the above that designing HV insulators (for both indoor and outdoor use) does not only depend on the insulator material, the pollution level of the relevant region and the voltage level at which the insulator will function, but also on the effect water droplets may have on the flashover voltage.

It is the purpose of the present paper to give an insight of the work being performed in our laboratory, for a wide range of water conductivities and a variety of droplet volumes. Polymeric materials of different degrees of surface roughness and resistivity were investigated. Experimental data is presented and possible explanations follow.

2.0 FORCE BALANCE AT THE DROPLET/POLYMER SURFACE INTERFACE

Condensation of droplets on the polymeric surface can come about from droplet germs. In Fig. 1, the forces exercised on the droplet are shown in cases where no applied electric 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 liquid and solid (δ_{SL}) [2]. With the application of an

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electric field, the droplet will deform because of an additional force. The tangential electric field on the polymeric surface creates a force on the surface of the droplet which causes a deformation. The droplet deformation influences the field distribution. (It is obvious that the deformation causes the droplet to become mechanically unstable and to eject water filaments from its vertices or coalesces with other droplets [3]). Local field enhancements may result and these in turn will cause micro-discharges between the droplets. In this way, the electro-chemical deterioration of the insulator surface begins. Hydrophobicity may locally be lost. It is to be remembered that it is not only the influence of the applied electric field on the shape of the droplet that counts, but also the influence of the disintegrated droplet on the electric field distribution. The voltage difference across the droplet will be diminished and micro-discharges will ensue. Since electro-chemical deterioration sets in, solvable nitrates resulting in a higher conductivity of the water droplets will appear. Dry zones will follow. One of the factors that has to be taken into account is the influence of the disintegrated droplet on the electric field distribution [4, 5].

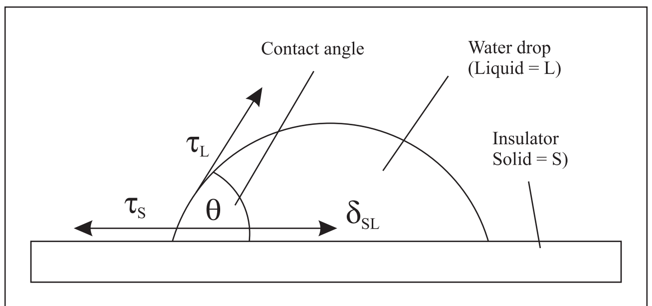

FIG. 1 FORCE BALANCE AT THE DROPLET/POLYMER SURFACE INTERFACE [2]

Hydrophobic polymeric surfaces are characterised by a low surface conductivity, low discharge activity and a higher flashover voltage, especially in a polluted environment. Less hydrophobic materials are prone to more PD activity, more dry zones and a lower flashover voltage. Hydrophilic surfaces, on the other hand, are characterised by intensive discharge activity, which in turn depends on the water conductivity [6].

3.0 EXPERIMENTAL ARRANGEMENT

The voltage was supplied from a 20 kV transformer (in practice, the transformer may deliver voltages up to 1.2 times of its nominal voltage without loss of the accuracy of the measurement. Therefore, we could consider that the applied voltages were accurate up to 24 kV). The electrodes used are shown in Fig. 2, where a top view is offered. The electrodes were made of copper and they had a half cylindrical shape with rounded edges. Their surfaces were smooth so that no irregularities were observed. The smoothness of the electrodes was essential in order to obtain uniform electric fields.

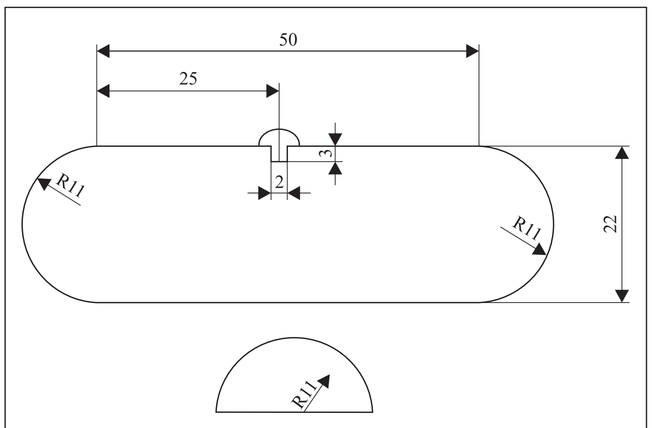

FIG. 2 TOP VIEW (ABOVE) AND CROSS SECTION (BOTTOM) OF THE ELECTRODES USED (ALL DIMENSIONS IN mm)

The water droplets were positioned on the polymeric 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 a syringe [7]. In Fig. 3 the droplet arrangements, used in this work, are shown. The polymeric materials used were PVC, silicone rubber and rubber. Measurements of surface roughness and resistivity were performed on the above materials. Measurements of surface roughness, performed with a device of type Perthen (Perthometer M4P0) gave a roughness of 0.25μm for PVC, 0.79μm for silicone rubber and 1.10 μm for rubber. Measurements of resistivity of the surface performed with the aid of a device of Megger BM25 type, gave a

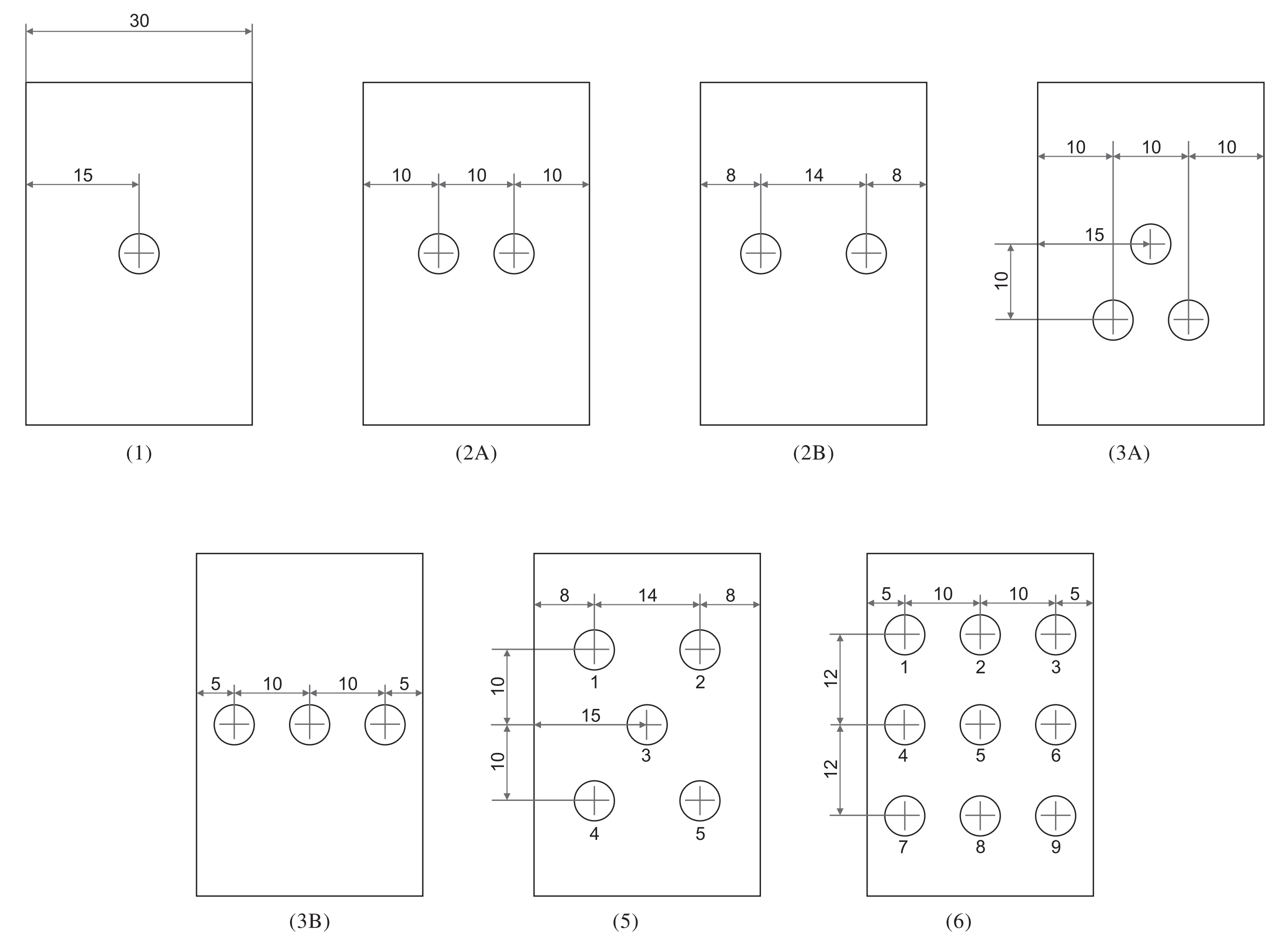

FIG. 3 TOP VIEW SHOWING THE DROPLET ARRANGEMENTS. STARTING FROM TOP LEFT, THE ARRANGEMENTS WERE NAMED AS ARRANGEMENT 1—WITH A SINGLE DROPLET, ARRANGEMENT 2A—WITH TWO DROPLETS, 10-10-10, ARRANGEMENT 2B—WITH TWO DROPLETS, 8-14-8, ARRANGEMENT 3A—WITH 3 DROPLETS IN THE FORM OF A TRIANGLE, ARRANGEMENT 3B—WITH 3 DROPLETS IN LINE, ARRANGEMENT 5—WITH 5 DROPLETS AND ARRANGEMENT 6—WITH 9 DROPLETS. ALL DIMENSIONS GIVEN ARE IN mm AND THEY SYMBOLISE THE DISTANCES OF THE DROPLETS FROM THE RESPECTIVE ELECTRODES AND THE DISTANCES BETWEEN THEM

resistivity of 206 GΩ for PVC, 3100 GΩ for silicone rubber and 2660 GΩ for rubber. The above given values of both roughness and resistivity were not isolated values but each of them was the mean of three measurements [8]. Regarding the measurements of resistivity, these were taken with an applied voltage of 5 kV with a distance of 1 cm between the measuring electrodes of the Megger device.

The various conductivities which were used for the experiments of the present work ranged from 1.7 μS/cm up to 2000 μS/cm for the droplets used. The conductivities were the result of mixing distilled water with appropriate quantities of NaCl. 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. In this work, results are presented with the above range of water conductivities. The reason we chose this range of conductivity values is because the natural rain conductivity lies generally between 50-150μS/cm and because testing with porcelain and glass insulators is carried out under conductivities of 2500 μS/cm. We thus believe that testing in the range of 1.7 – 2000 μS/cm covers more or less all the above conditions.

The droplet volume used in this work was 0.1 ml. This droplet volume was chosen because bigger volumes were already investigated [9, 10] and small droplet volumes may cause remarkable reductions in flashover voltage.

4.0 EXPERIMENTAL INVESTIGATION

The experimental procedure consisted of positioning the droplets on a polymer surface. For the experiments we chose arrangements of 1, 2, 3, 5 and 9 droplets. The droplet volumes were chosen so that more realistic conditions could be simulated. The electrodes were positioned at a distance of 3 cm parallel from each other so that the positioning of droplets between them would be easy. The insulating surface was not treated in any way but it was used as it was received from the manufacturer. After the positioning of droplets on the insulating surface, the voltage was raised slowly until flashover occurred. After that—and with new droplets on a clean surface—the voltage was raised upto the previous breakdown value minus 1.2 kV so that no new breakdown would occur. At this voltage, the droplet arrangement could stay for 5 min. If no new flashover occurred, the voltage was raised thereafter by 0.4 kV and the procedure was repeated until flashover occurred. This was the flashover registered. The reason we allowed the voltage for 5 min at each value was to see the deformation of the droplets and the starting of PD. Needless to say, that the aforementioned procedure was repeated for reproducibility but no statistical treatment of the data was carried out. This is because the primary aim of the present work was not the detailed statistical treatment of the results but to study the variation of the behaviour of water droplets with parameters, such as the positioning of droplets, their conductivity, the droplet volume and the roughness of the insulating surface.

5.0 RESULTS

At first, the experiments were performed without any droplets on the insulating surfaces. This was because we wanted to have some flashover values of reference. The flashover voltages without any droplets were 23 kV, 25 kV and 24 kV (± 0.5 for all materials) for PVC, silicone rubber and rubber respectively. The flashover voltage values of the three tested materials were very similar.

The placement of a droplet on a polymeric surface between the electrodes and the application of voltage results in an oscillation and thereafter the elongation of it. The oscillation of the droplet depends on the roughness of the polymeric surface and it is more pronounced in the case of silicone rubber. It is speculated that this happens because of the greater hydrophobicity of silicone rubber. Since the roughness of silicone rubber is not the greatest (compared to the other materials), it is reasonable to assume that droplet oscillation is due to the interplay of the two aforementioned factors. With the increase of the number of the droplets, the droplets oscillate even more. Droplet oscillation is more intense on the less rough surfaces. Increasing the water conductivity leads to lower values of flashover voltages. Water paths between the droplets are formed during the tests. Such paths remain even without the further application of voltage. It was observed that the break-up of a single droplet was much more violent than the break-up of the arrangements with more droplets. A point to remember is that, with PVC, there is a far greater damage of the material than with the other two polymers.

Figs. 4-8 show the graphs of some of the droplet arrangements. It is obvious that the droplet conductivity affects the flashover voltage, as was also noted by others [11]. Silicone rubber had, in most experiments, better performance than the other two materials. It is only with the droplet arrangement 3A that rubber does equally well or even better than silicone rubber. This may be attributed to the fact that, for this particular arrangement, rubber, being rougher than the other two polymers, allows the droplets to oscillate to a lesser extent.

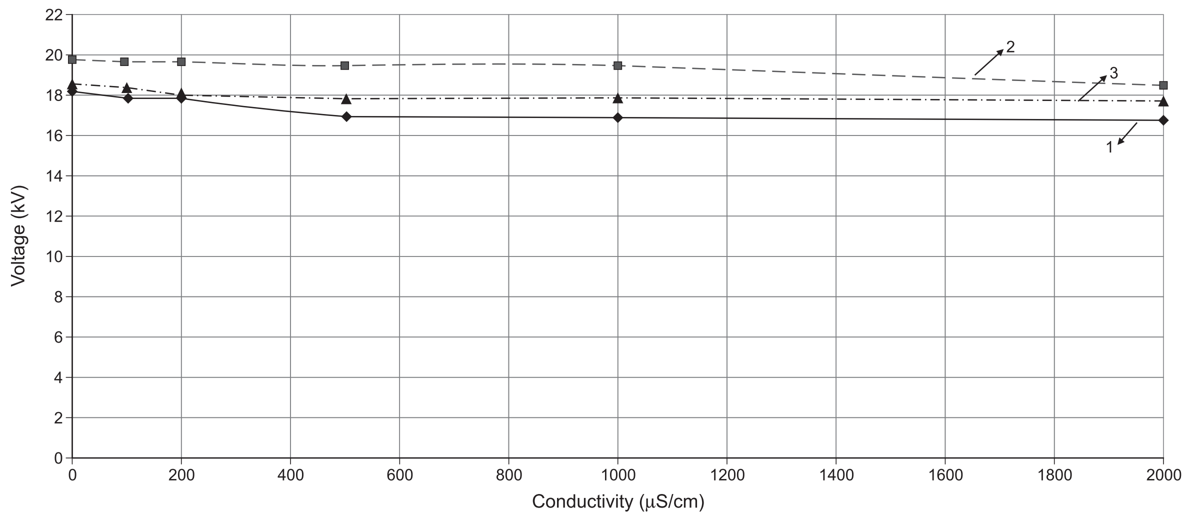

FIG. 4 FLASHOVER VOLTAGE FOR VARIOUS CONDUCTIVITIES. DROPLET VOLUME 0.1 ml, 1 - PVC (1), 2 – SILICONE RUBBER (1), 3 - RUBBER (1)

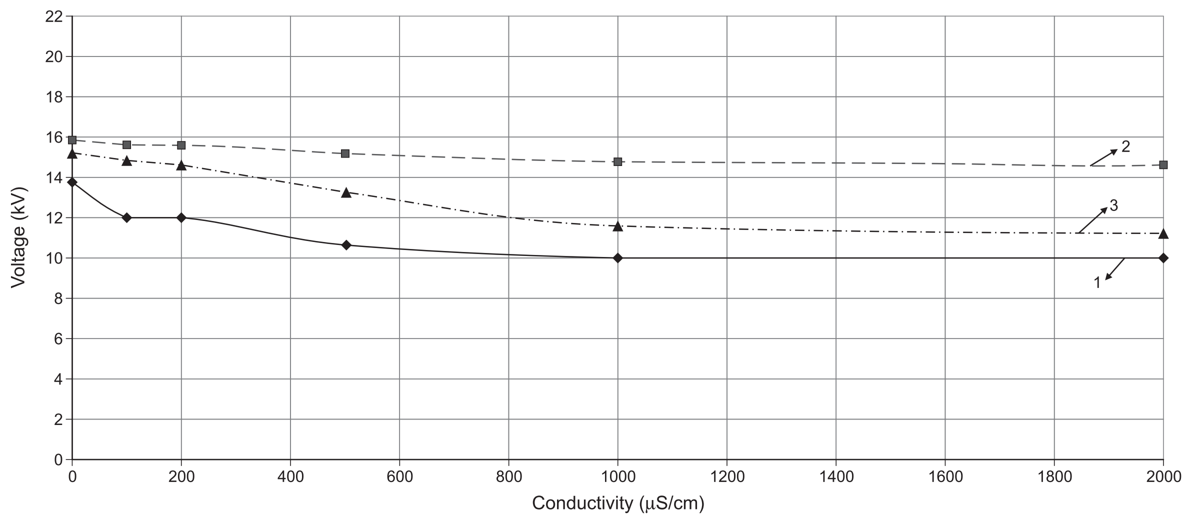

FIG. 5 FLASHOVER VOLTAGE FOR VARIOUS CONDUCTIVITIES. DROPLET VOLUME 0.1 ml, 1 – PVC (2A), 2 – SILICONE RUBBER (2A), 3 - RUBBER (2A)

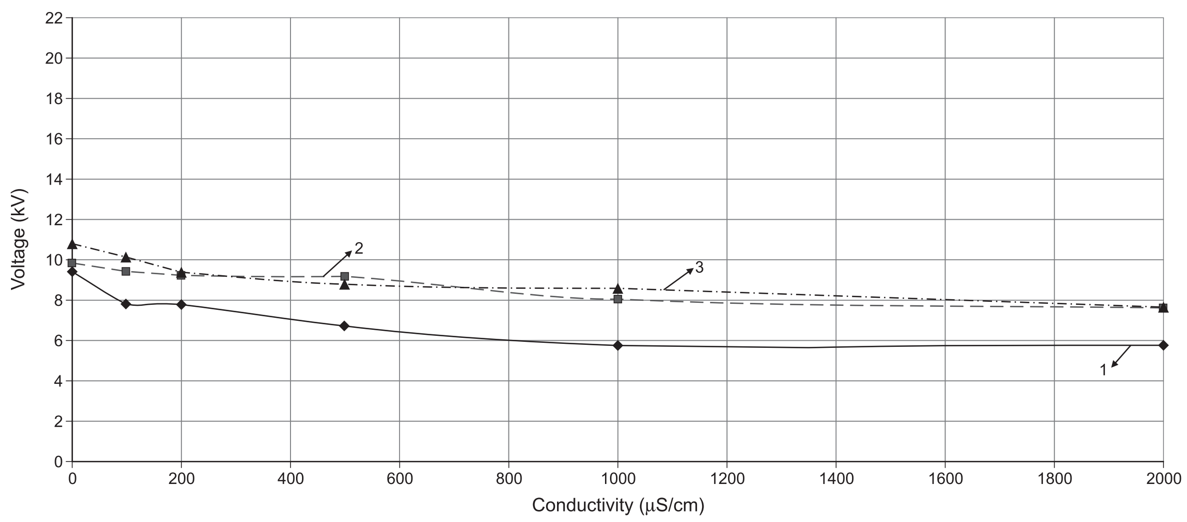

FIG. 6 FLASHOVER VOLTAGE FOR VARIOUS CONDUCTIVITIES. DROPLET VOLUME 0.1 ml, 1—PVC (3B), 2—SILICONE RUBBER (3B), 3—RUBBER (3B)

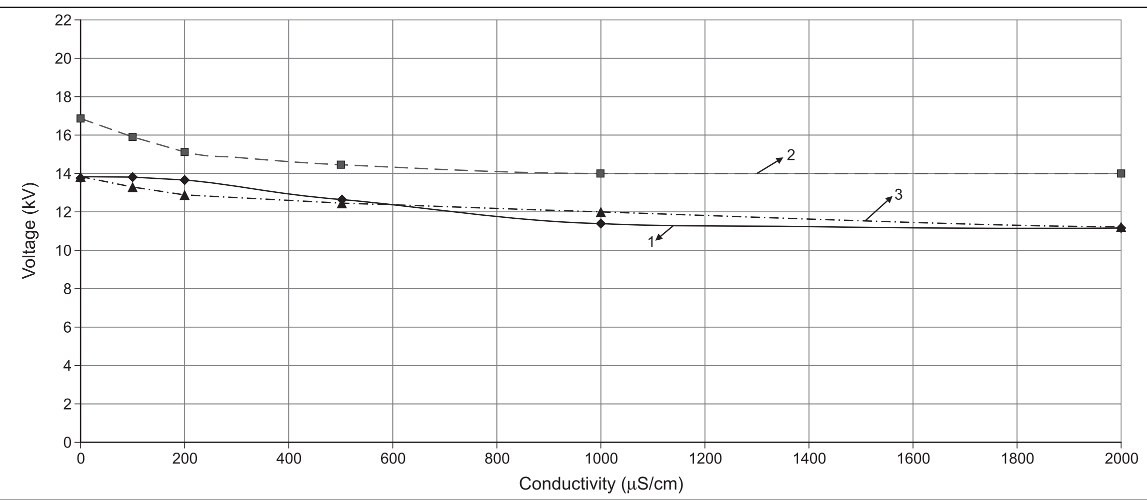

FIG. 7 FLASHOVER VOLTAGE FOR VARIOUS CONDUCTIVITIES. DROPLET VOLUME 0.1 ml, 1—PVC (5), 2—SILICONE RUBBER (5), 3—RUBBER (5)

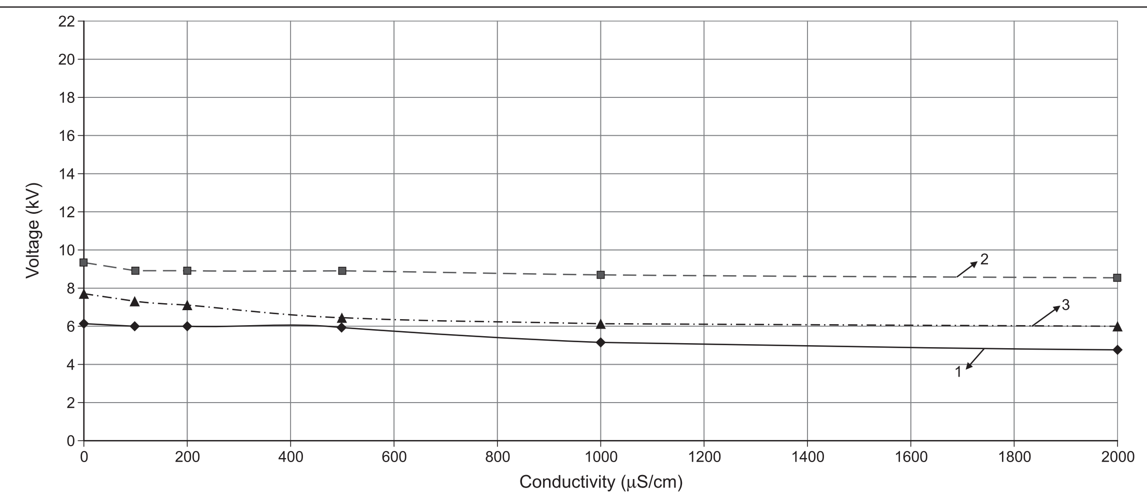

FIG. 8 FLASHOVER VOLTAGE FOR VARIOUS CONDUCTIVITIES. DROPLET VOLUME 0.1 ml, 1—PVC (6), 2—SILICONE RUBBER (6), 3—RUBBER (6)

Generally, one may say that silicone rubber shows a better behaviour than the other two polymers. Figs. 9–11 show the flashover voltage variation with droplet conductivity for all used arrangements for each single polymer. The reason for this group of curves is to see whether the flashover voltage is affected more from the number of droplets or from the droplet arrangement. It is evident that the flashover voltage is affected from the droplet volume. In all cases, there is a reduction of flashover voltage with the increase in the droplet volume. If, however, we compare the curves of the arrangements 3B and 5, we observe that the flashover voltage in the latter arrangement is higher than the flashover voltage of the former. This means that the droplet arrangement—at least in some cases—is more important than the total droplet volume. It is assumed that in the case of the 3B arrangement, the electrical field will cause elongation of the droplets; therefore the three droplets will form conductive paths more easily than the five droplets in the arrangement 5. It is to be noted that similar results were observed in publications [9, 10] albeit with droplets of 0.2 ml and 0.3 ml.

Droplets which are near the electrodes cause a lower flashover voltage, i.e. the electrodes play a dominant role. Droplets under the effect of electrical field tend to coalesce, elongate and extend and this is due to the field developed at

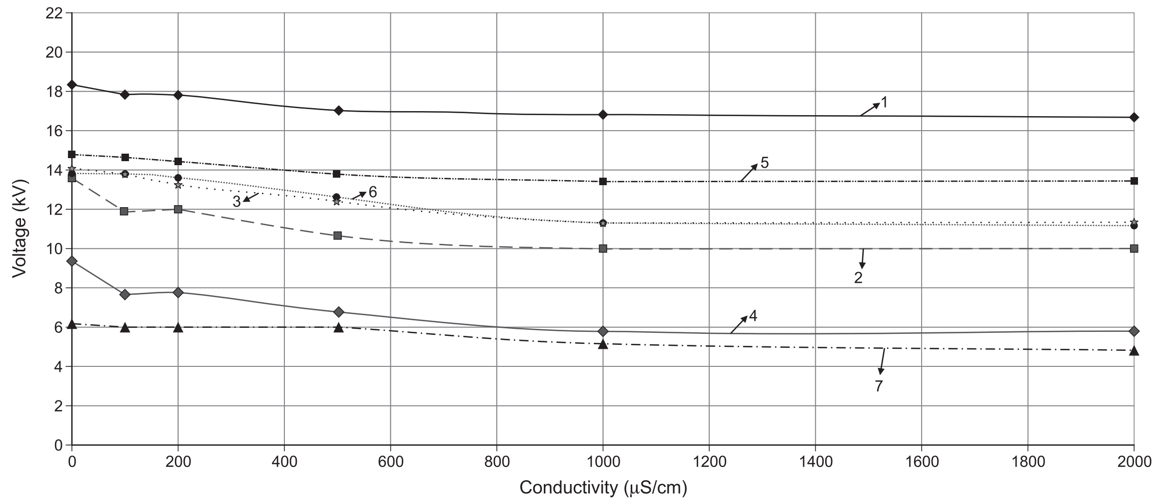

FIG. 9 FLASHOVER VOLTAGES FOR VARIOUS CONDUCTIVITIES AND POSITIONINGS OF THE DROPLETS. 1—PVC (1), 2—PVC (2A), 3—PVC (2B), 4—PVC (3B), 5—PVC (3A), 6—PVC (5), 7—PVC (6)

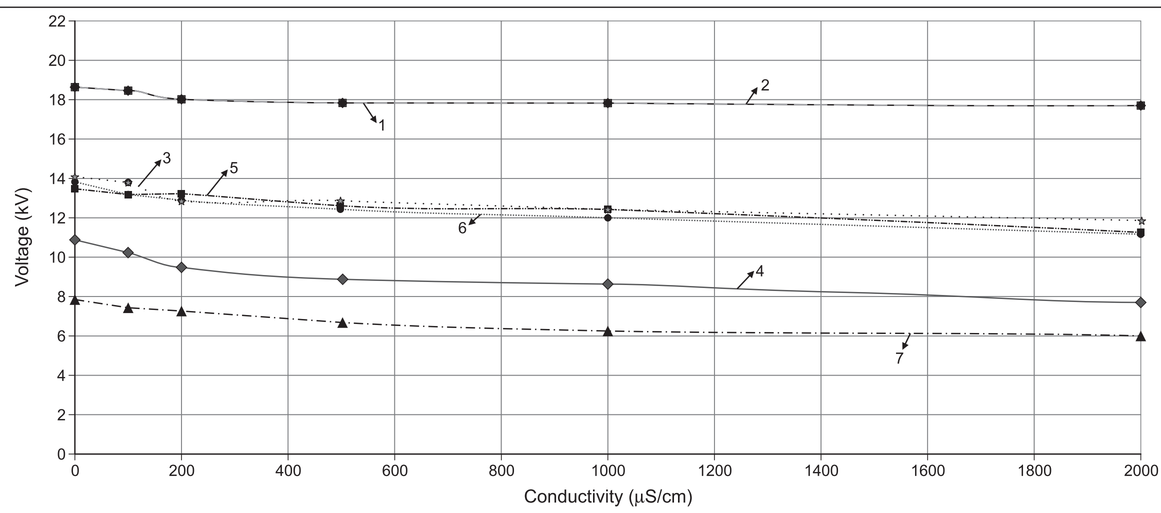

FIG. 10 FLASHOVER VOLTAGES FOR VARIOUS CONDUCTIVITIES AND POSITIONINGS OF THE DROPLETS. 1—RUBBER (1), 2—RUBBER (2A), 3—RUBBER (2B), 4—RUBBER (3B), 5—RUBBER (3A), 6—RUBBER (5), 7—RUBBER (6)

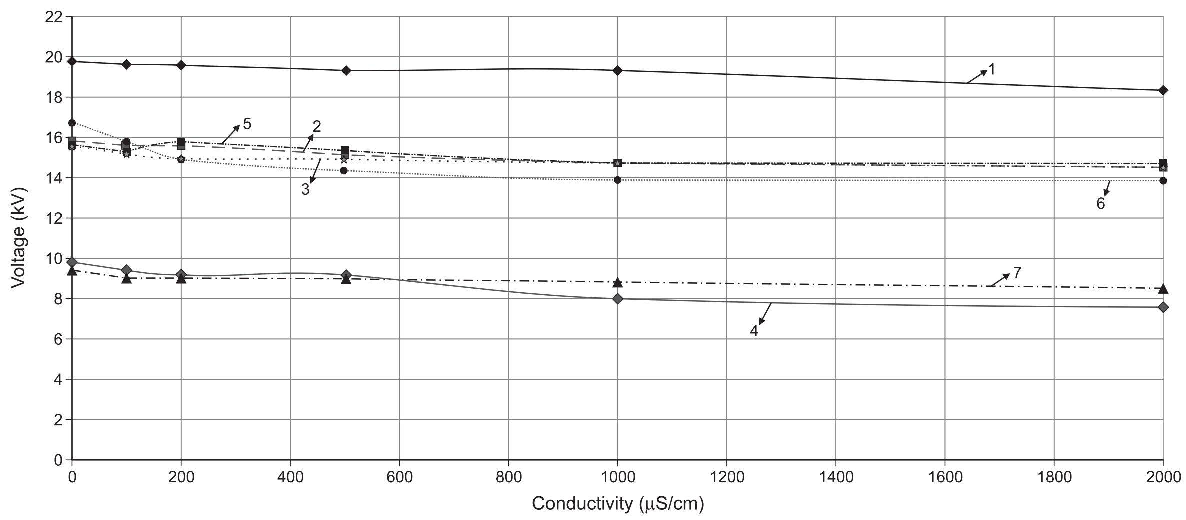

FIG. 11 FLASHOVER VOLTAGES FOR VARIOUS CONDUCTIVITIES AND POSITIONING OF THE DROPLETS. 1—SILICONE RUBBER (1), 2—SILICONE RUBBER (2A), 3—SILICONE RUBBER (2B), 4—SILICONE RUBBER (3B), 5—SILICONE RUBBER (3A), 6—SILICONE RUBBER (5), 7—SILICONE RUBBER (6)

the "triple point". Since the greatest field intensifications are noticed in the so-called "triple points", i.e. at the point where air, polymer and the droplet meet together and/or where the droplet, polymer and electrode meet together, a lowering of flashover voltage is to be expected.

6.0 DISCUSSION

Some parameters affecting the behaviour of the water droplets on polymeric surfaces were investigated. The increase of droplet conductivity causes the decrease of flashover voltage, this being a valid observation, irrespective of the polymer used. The surface roughness affects the flashover voltage in a positive way when the number of droplets is large. The rough surface hinders the oscillation of droplets and therefore they cannot easily create conducting paths. An increase in droplet volume implies a decrease of flashover voltage [12]. The positioning of droplets w.r.t. the electrodes is of great importance. This observation is in agreement with previously published results [9, 10]. Silicone rubber proved to be a better material than PVC or rubber. This may be due to its hydrophobicity, although in the context of this series of tests one could not see its regenerative LMW (low molecular weight) possibilities [13]. The forming of water paths follows the direction of the applied field (Fig. 12). As said before, the "triple points" play a crucial role in determining the flashover voltage, i.e. the droplet arrangement is—at least in some cases—of perennial importance as to the behaviour of the droplets on polymeric surfaces.

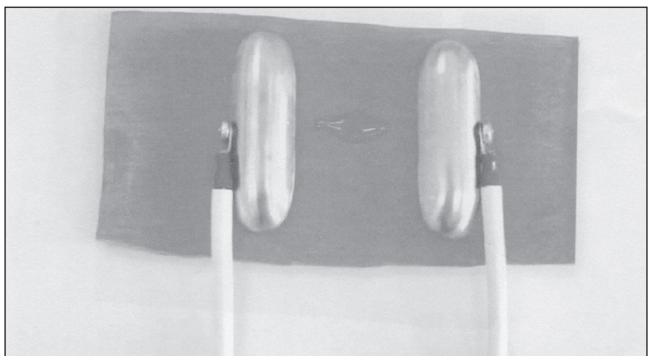

FIG. 12 ARRANGEMENT WITH A SINGLE DROPLET. SILICONE RUBBER USED, DROPLET VOLUME 0.1 ml, CONDUCTIVITY 1.7 μS/cm

Thus, droplet conductivity, surface roughness, positioning of droplets and droplet volume are some of the factors affecting the flashover voltage. The polymer we use also plays a significant role. Hydrophobic materials, such as silicone rubber, seem to show their superiority in all tests performed. Even in the short duration tests described here, silicone rubber indicates that it is better than PVC or rubber. Such data confirms previously published work [14].

7.0 THOUGHTS ON POSSIBILITIES OF FURTHER RESEARCH

It is true that what was presented here was verified in the context of the experimental work in our laboratory using water droplets of various volumes and water droplet arrangements different from the ones presented in this paper [8, 9, 10, 15, 16]. The above mentioned parameters (droplet conductivity, surface roughness, positioning of droplets and droplet volume) seem to affect water droplets under electric fields, and when such droplets are on an inclined plane. It is also evident from the results of the present work that the flashover voltage depends on the polymeric material used. In that respect, the hydrophobic properties of silicone rubber are rendered important. From the aforementioned references, less damage to the surface of silicone rubber was observed. This implies that the hydrophobic properties play a crucial role even with experiments of a rather short duration, as was the case in the present paper.

Nevertheless, much remains to be done. A greater variety of polymeric materials may validate better the conclusions of this work. Such polymeric materials can be used both in their virgin form and/or as aged materials. The parameters investigated in this work, should also be studied with aged polymeric surfaces. A more thorough study should be performed on the mechanism of flashover, both with virgin and aged polymeric surfaces. Given that the contamination on insulator surfaces is not uniform and that the boundaries of the dry bands are not parallel [17], the mechanism of flashover should be re-examined, especially in the light of a recent work claiming that—for hydrophobic surfaces—discharges on insulator surfaces are similar to low pressure glow discharges [18]. Attention should also be paid to the mechanism of loss of hydrophobicity due to the local discharges.

Small discharges on the insulator surface is another interesting field of further work. The question, as to whether there exists a lower limit of discharge activity below which no practical ageing of the insulator surface takes place, is a pertinent one and should be researched. This question, albeit rather neglected for outdoor and indoor insulation, may elucidate many aspects of early ageing, as reported in [18, 19, 20]. The question of whether ageing exists below a certain power of discharges and/or below a certain level of applied voltage is a vital one, since there is currently an increased interest not only in the domain of outdoor and indoor insulators but also in the domain of cables [21, 22].

8.0 CONCLUSIONS

In this paper, some of the parameters affecting the behaviour of water droplets on polymeric surfaces were investigated. It was shown that water conductivity, polymer surface roughness and droplet volume play an important role in determining the behaviour of the droplets under the influence of an electrical field. The positioning of the droplets w.r.t. to the electrodes is also a factor not to be neglected.

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