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DETERIORATION PHENOMENA ON POLYMERIC INSULATING SURFACES DUE TO WATER DROPLETS

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In this publication the problems arising from the application of uniform *ac* electric fields on water droplets, which are on polymer surfaces, are discussed. Polymeric materials such as silicone rubber, PVC and rubber were used for the experimental work. The deterioration phenomena — due to partial discharges (PD) and localized arcs — were studied in terms of water conductivity, polymer surface roughness, droplet volume and droplet position with respect to the electrodes. All the four mentioned parameters affect the flashover voltage. Perhaps the most unexpected result was that the positioning of the droplets with respect to the electrodes plays a more important role than the droplet volume. A comparison between the aforementioned materials was made and commented upon.

K e y w o r d s: water droplets, polymeric surfaces, uniform field, outdoor insulation, indoor insulation, pollution, contamination

1 INTRODUCTION

It is known that water droplets on the surface of a non-ceramic insulator may provoke — under applied electric field deterioration even in conditions of low pollution. This is due to the fact that water droplets on a polymer surface locally increase the applied electric field. Local field intensifications will lead to partial discharges and/or localized arcs that in turn render possible creation of dry bands on the polymer surface. Bridging of individual dry bands by means of local arcs will finally lead to a complete flashover. This is a mechanism valid for both outdoor and indoor insulation although each of the aforementioned categories has its own peculiarities [1–3]. Generally speaking, a combination of water droplets and dust-like impurities on the surface of an insulating surface may lead to a conducting contamination layer which may in turn cause a significant reduction of the flashover voltage. In designing thus high voltage insulators (for both indoor and outdoor use) we must take into account not only the pollution level which might be encountered, the insulator material and the voltage level but also the influence of water droplets on the flashover voltage.

The pollution in hydrophobic surfaces has already been studied extensively and it has been observed that, under heavy contamination, the insulator surface may loose its hydrophobicity [4–6]. In special cases, *eg* with silicone rubber, hydrophobicity may recover due to the diffusion of low molecular weight substances from the bulk of the insulator to its surface [5, 6].

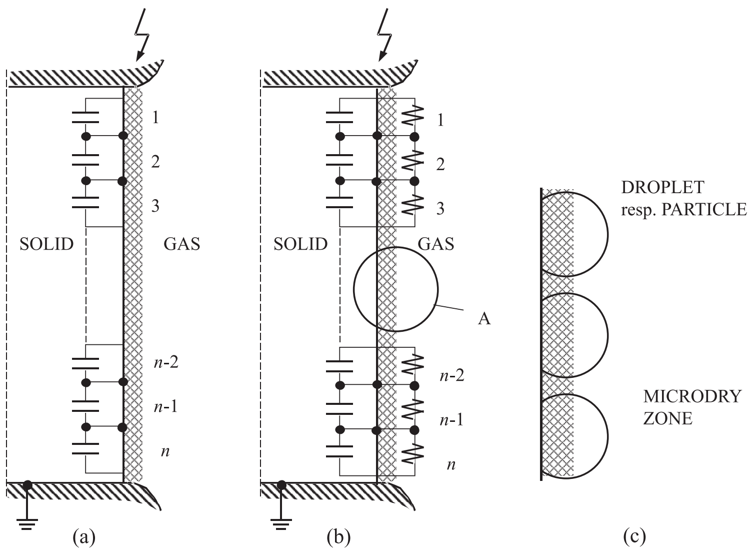

Fig. 1. Modelling of an insulating surface: (a) dry and clean conditions, (b) wet and/or contaminated conditions, (c) details of a wet hydrophobic and/or contaminated surface (droplets, resp. conducting particles).

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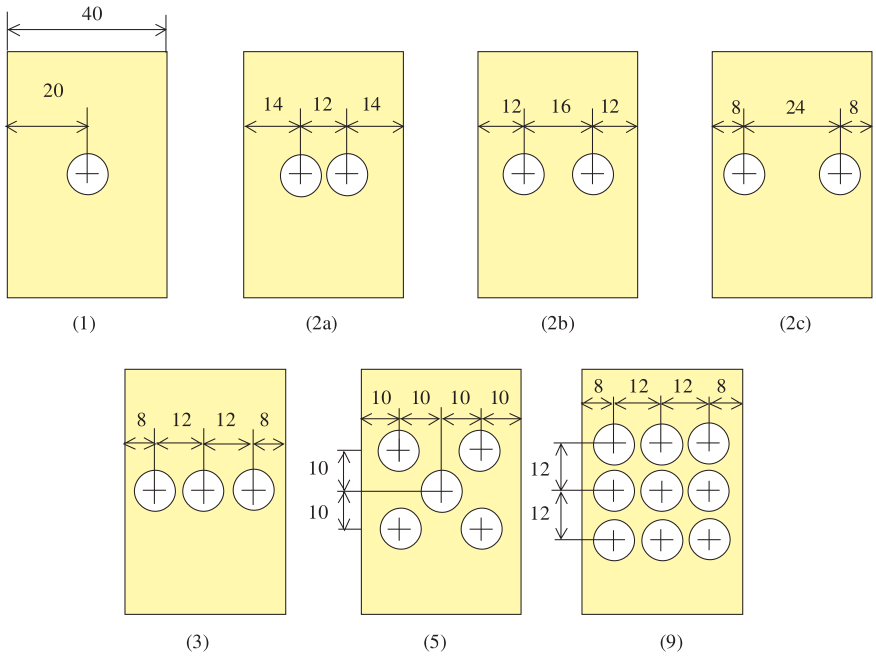


Fig. 2. Top view showing the droplet arrangements. Starting from top left, the arrangements were named as arrangement (1) (with one droplet), arrangement (2A) (with two droplets, 14-12-14), arrangement (2B) (12-16-12), arrangement (2C) (8-24-8), arrangement (3) (with 3 droplets), arrangement (5) (with 5 droplets) and arrangement (9) (with 9 droplets). All dimensions given are in mm and they symbolize the distances of the droplets from the respective electrodes and the distances between them.

As a general rule, one might say that in both cases — of light and heavy pollution — discharges or localized arcs may start from water droplets. Consequently, research on the behaviour of water droplets under the influence of the electric field is important in understanding some of the factors affecting the ageing mechanism of polymeric insulators. In the context of the present paper, we studied such a behaviour taking into account parameters such as water conductivity, polymer surface roughness, droplet volume and droplet position with respect to the electrodes. A uniform electrode arrangement was used.

2 MODELLING OF SURFACE CONTAMINATION

A dry and clean surface of a solid insulator can be represented by a chain of n capacitors where the applied electric field is evenly distributed. A wet and/or contaminated surface, however, can be represented by a chain of n capacitors and n resistors in parallel. Such a superposition of ohmic and capacitive components is shown in Fig. 1. Admittedly, this model is a simple one since it does not take into account the *shape* and the *distribution* of droplets on the insulating surface. It is, however, an adequate tool for a first approach to the problem of wet insulating surfaces. The droplets and/or conducting particles on the insulator surface cause a change in electric field distribution and the local overstressing in the gaseous domain between the droplets may give rise to local PD (which may be called surface partial discharges) [7]. Local PD may lead to chemical by-products and deterioration of the surface. The latter has as a consequence an increase of roughness of the surface and a loss of hydrophobicity. The insulator surface absorbs more water and creates a humidity layer of increasing thickness. Moreover, the conductivity of the water droplets — because of the by-products, which are presumably soluble nitrates — increases. This in turn leads to an increased leakage current and a worse flashover performance. Such an ageing mechanism can be common to both indoor and outdoor insulations [3, 8, 9].

The tangential electric field on the surface of the insulator creates a force on the surface of the droplet which causes its deformation. Following that, the droplet may influence the field distribution and local field enhancements may result. The latter can cause micro-discharges between the droplets. Electrochemical deterioration of the surface may ensue and lead to partial loss of hydrophobicity. Details on this mechanism were given in [8, 10].

3 EXPERIMENTAL ARRANGEMENT AND PREPARATION

Our aim in the context of the present paper is to study the behaviour of water droplets under the influence of an applied electric field. 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 measurement. In this way, we may consider that the applied voltages are accurate up to 24 kV. This value was not exceeded during the whole series of the experiments. The electrodes used were made of copper and they had a half cylindrical shape with

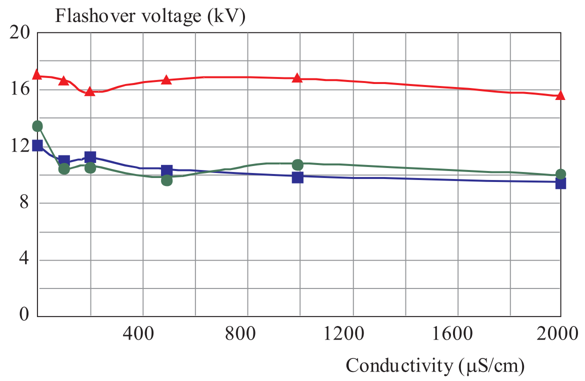


Fig. 3. Flashover voltage for various conductivities. Droplet volume 0.3 ml, squares refer to PVC (2A), triangles to silicone rubber (2A) and circles to rubber (2A).

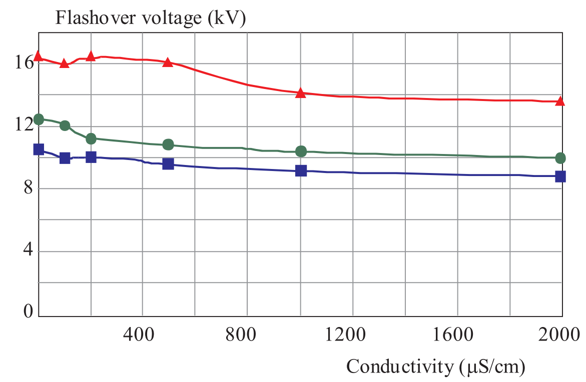


Fig. 4. Flashover voltage for various conductivities. Droplet volume 0.3 ml, squares refer to PVC (2B), triangles to silicone rubber (2B) and circles to rubber (2B).

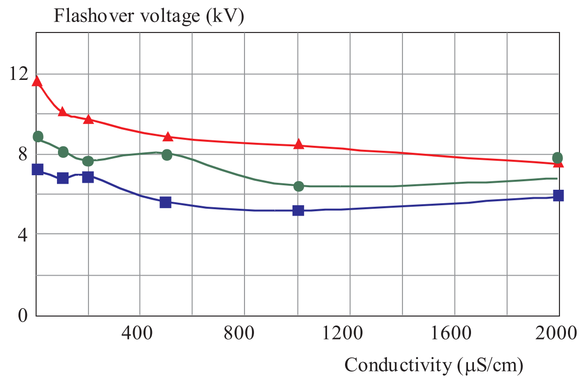


Fig. 5. Flashover voltage for various conductivities. Droplet volume 0.3 ml, squares refer to PVC (3), triangles to silicone rubber (3) and circles to rubber (3).

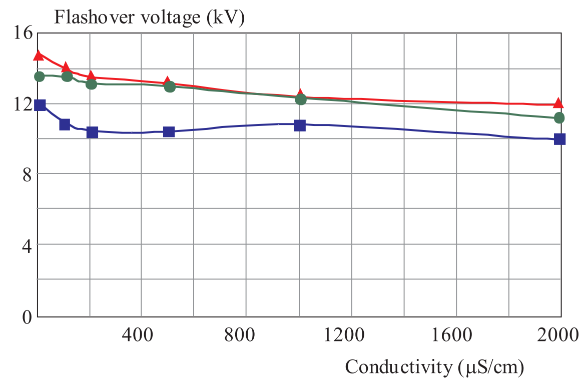


Fig. 6. Flashover voltage for various conductivities. Droplet volume 0.2 ml, squares refer to PVC (5), triangles to silicone rubber (5) and circles to rubber (5).

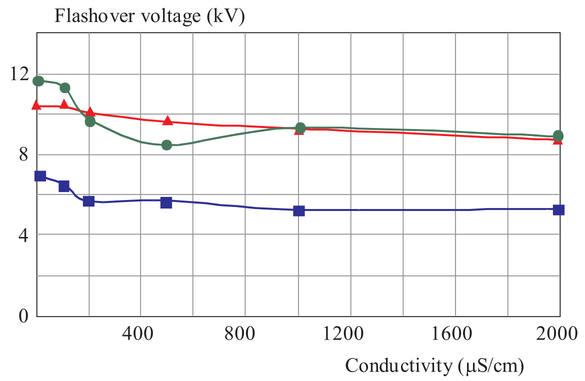


Fig. 7. Flashover voltage for various conductivities. Droplet volume 0.2 ml, squares refer to PVC (9), triangles to silicone rubber (9) and circles to rubber (9).

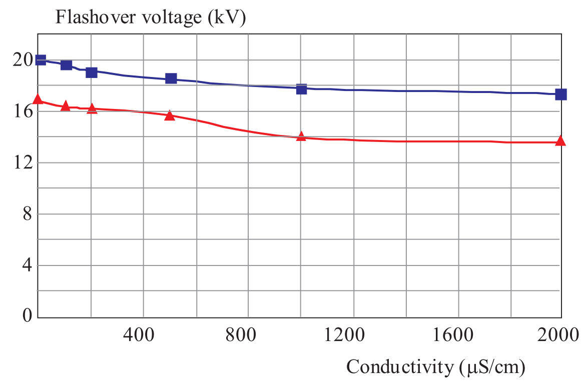


Fig. 8. Flashover voltages for various conductivities. Triangles symbolize a droplet of 0.3 ml and squares a droplet of 0.2 ml (PVC used).

rounded edges. Attention was paid so that their surfaces were smooth with no asperities or any form of irregularities whatsoever. That was vital in order to obtain a uniform electric field.

The water droplets were accurately positioned on the polymeric material 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. Detailed information on the way the droplets were positioned on the polymer surface is given in [11]. Figure 2 shows the droplet arrangements used for this work.

The polymeric materials used were PVC, silicone rubber and rubber. These are materials easily found in the commerce. Measurements of the surface roughness and of resistivity were performed with the above-mentioned materials. Measurements of the surface roughness, performed with an appropriate device of type Perthen (Perthometer M4P), gave a roughness of 0.25 μm for PVC, 0.79 μm for silicone rubber and 1.10 μm for rubber.

Measurements of the resistivity of the surface, performed with the aid of a device of Megger BM25 type, gave a resistivity of 206 GΩ for PVC, 3100 GΩ for silicone rubber and 2660 GΩ for rubber. Let us say that the above given values of both roughness and resistivity were not isolated values but, each of them, the mean of three measurements [11]. Let us also say that the measurements 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 this paper were the results of mixing distilled water with appropriate quantities of NaCl. Water conductivities of 1.7, 100, 200, 500, 1000 and 2000 μS/cm for the droplets were used. The measurements of the various water conductivities were made with the aid of an electronic measuring device of conductivity of type WTW inoLab cond Level 1. Six samples with water conductivities as mentioned above were prepared [11].

4 EXPERIMENTAL METHOD

We studied the behaviour of water droplets on a polymer surface. For the experiments we chose arrangements of 1, 2, 3, 5 and 9 droplets. The droplets volumes were 0.2 and 0.3 ml. Such volumes were chosen in order to better simulate the realistic conditions. The electrodes were positioned at a distance of 4 cm parallel from each other so that the positioning of droplets between them would be easy.

The parameters of the experiments were the positioning of the droplets, their conductivity, the droplet volume and the insulating surface. The insulating surface was not treated in any way but it was used as it was received from the manufacturer. The experimental method followed was — after putting the droplets on the surface — to raise slowly the voltage until breakdown occurred. After that and after cleaning the surface, putting new droplets on it, we raised the voltage up to the previous breakdown value minus 1.2 kV so that no new breakdown would occur. At this voltage value the arrangement could stay for 5 min. If no breakdown occurred, the voltage was raised by 0.4 kV and the procedure was repeated until a breakdown occurred. This was the breakdown value which was registered. The reason we allowed the voltage for 5 min at each value was because we wanted to give the necessary time interval for the droplet(s) to deform and for the PD to start. Photograph 1 (a-g) shows the various droplet arrangements.

It must be said at this stage that what is presented in the present work is a first approach, in our laboratory, to the problem of water droplets on polymeric surfaces under the influence of an electrical field. Not many repeated tests were performed, so a statistical analysis of the measured data at this stage is not possible. In the context of this work we try, first of all, to qualitatively approach the various droplet arrangements and to have a feeling as to how the aforementioned parameters (conductivity, droplet volume *etc*) affect the droplet behaviour. A statistical analysis will follow when more data will be collected. It is true that at the moment, no definite conclusions may be drawn for the differences between the means of data measured at different conductivities of water droplets and whether such differences are significant. On the other hand, it can be said that the present work offers a strong indication of the tendencies the droplet behaviour follows because of the aforementioned parameters. For the sake of brevity, in this paper only a small number of figures are included.

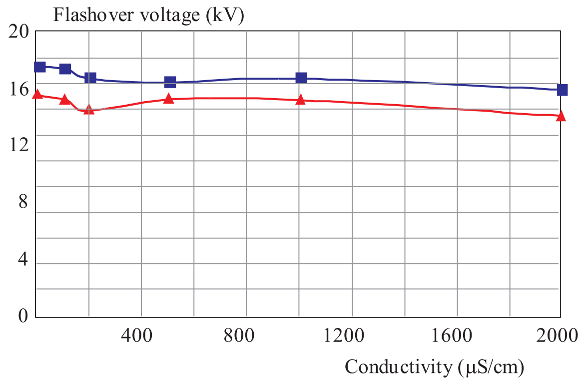
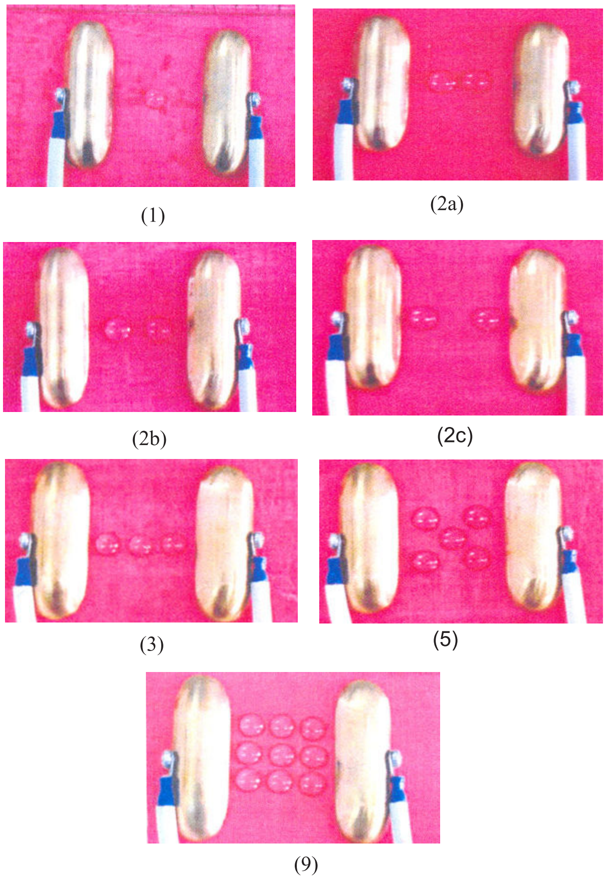


Fig. 9. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (silicone rubber used, droplet arrangement 2A).

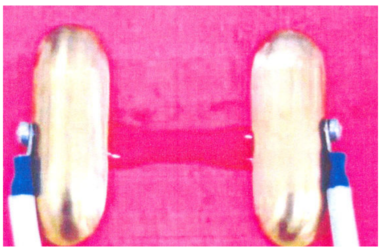
5 EXPERIMENTAL RESULTS

The first of all experiments were performed without any droplets between the electrodes. This was done in order to have some values of reference and also in order to see whether any number of droplets between the electrodes would result in a reduction of the flashover voltage. The flashover voltages without any droplets were 23 kV (±0.5), 25 kV (±0.5) and 24 kV (±0.5) for PVC, silicone rubber and rubber respectively. We realize that the flashover values of the three materials were not that far from each other. Since it is impossible to refer to all the results of our research in the context of this paper, we will concentrate on some representative ones.

Figures 3–7 show the graphs of the various droplet arrangements (it must be said at this point that we preferred to present the results in figures rather than in tables because we think that the former transmit better the gist of the paper). It is evident that the droplet conductivity plays an important role in determining the flashover voltage. In most experiments, silicone rubber performed better than the other two materials. In the arrangements with 5 and 9 droplets, however, silicone rubber was not as good as rubber. Probably, with increasing number of droplets, the roughness of rubber — which is greater than the roughness of PVC and silicone rubber — plays a determining role since it allows the droplets to oscillate less [12]. Attention should be drawn on this: the droplet movement — under the influence of the electric field — is hindered by the surface roughness. This, however, is an observation concerning polymeric surfaces as received from the manufacturer and *not* aged surfaces. It seems though that silicone rubber has, generally speaking, a better performance than the other two materials under the same conditions of humidity. The superiority of silicone rubber is probably due to its hydrophobicity. A vital consequence of the latter is that its contact angle Θ_r is larger than the angle of the other tested materials.



Photograph 1. (a) Arrangement (1), (b) arrangement (2A), (c) arrangement (2B), (d) arrangement ((2C), (e) arrangement (3), (f) arrangement (5), (g) arrangement (9).



Photograph 2. Arrangement with three droplets. Final stage. Silicone rubber used, droplet volume 0.2 ml, conductivity $500\,\mu$S/cm.

Figures 8–11 are indicative of the influence of droplet volume on the flashover voltage. The increase of droplet volume causes a decrease of flashover voltage irrespectively of the material used. This is due to the fact that an increase of droplet volume decreases the distance between the droplet and the electrode and consequently a discharge (or an arc) is being formed more easily [13].

Figures 12–14 show the influence of positioning of the droplets with respect to the electrodes. Although more tests are needed in order to reach definite conclusions, it is fitting to say that relatively low flashover voltages are observed when the droplets are near the electrodes. One can draw parallels between this droplet behaviour and the behaviour of enclosed cavities in a solid insulation in which one of the boundaries is the metallic electrode [14, 15]. In both cases the emission of electrons and/or the uneven field distribution are more pronounced. The uneven field distribution is the result of field maxima which occur at the points better known as "triple points", *ie* at the common points where air, polymeric insulation and metallic electrode meet each other [16].

If we compare the curves of the droplet arrangements with 3 and 5 droplets, we observe that whereas for the case with the 3 droplets of 0.2 ml each the volume of the water is 0.6 ml and in the case of 5 droplets of 0.2 ml each is 1 ml, the flashover voltage is smaller in the former case than that of the latter. This is true for all three materials used. This indicates that the positioning of the droplets plays greater role than the total droplet volume. If we compare the curves of the droplet arrangements with 3 (of 0.2 ml each) and 9 (of 0.2 ml each) droplets, we observe that whereas the total droplet volume is three times greater in the latter case, the flashover voltage is comparable in these two droplet arrangements. This, in our opinion, verifies the previous statement. Let us note again, that not all results obtained can be shown in the context of this paper.

Generally speaking, with more than one droplets, the droplets under the influence of the field first start oscillating, then they join with each another and afterwards also with the electrodes creating thus a water path bridging the gap spacing without, however, arcing or breakdown. In some cases the water started boiling which resulted to its partial evaporation. Dry zones were created, micro-discharges and a bridging between the electrodes appeared (*eg* photograph 2). In the case of small water conductivity, the aforementioned water path behaves like a load (*ie* a resistance connecting the two electrodes). The smaller the conductivity, the greater the power consumed at this load. The current passing through such a water path (of small conductivity) means practically the increase of temperature of the water because of the power loss in the load. Consequently, the temperature developed in such a water path is enough so that the water starts boiling. This leads to the evaporation of some quantity of water and subsequently the water path becomes narrower and dry zones result. Generally, one may say that a predominant factor influencing the droplet behaviour is the available electrical energy as well as the conductivity of water.

6 CONCLUSIONS AND PLANS FOR FUTURE RESEARCH

Some basic parameters affecting the behaviour of the water droplets on polymeric surfaces were discussed, namely,

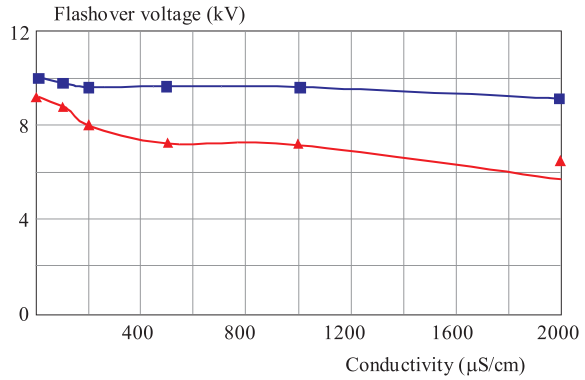


Fig. 10. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (PVC used, droplet arrangement 2C).

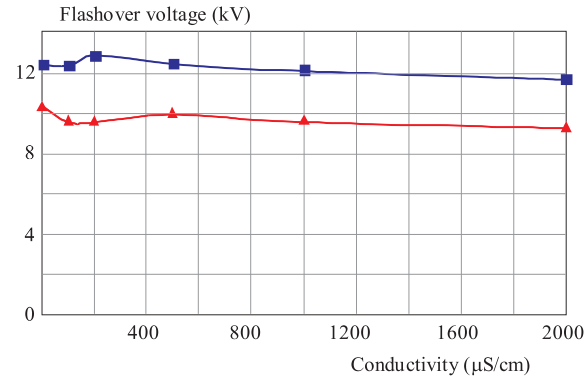


Fig. 11. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (silicone rubber used, droplet arrangement 2C).

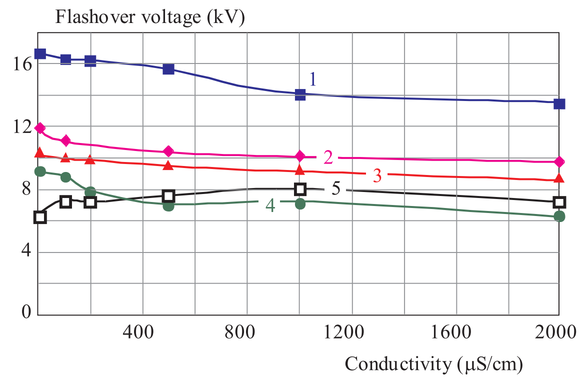


Fig. 12. Flashover voltages for various conductivities and positionings of the droplets. 1 PVC–(1), 2 PVC–(2A), 3 PVC–(2B), 4 PVC–(2C), 5 PVC–(5) (in all experiments droplets of 0.3 ml were used).

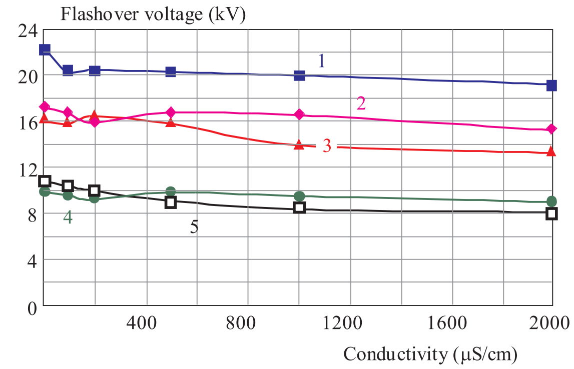


Fig. 13. Flashover voltages for various conductivities and positionings of the droplets. 1 SiR–(1), 2 SiR–(2A), 3 SiR–(2B), 4 SiR–(2C), 5 SiR–(5) (in all experiments droplets of 0.3 ml were used, SiR means silicone rubber).

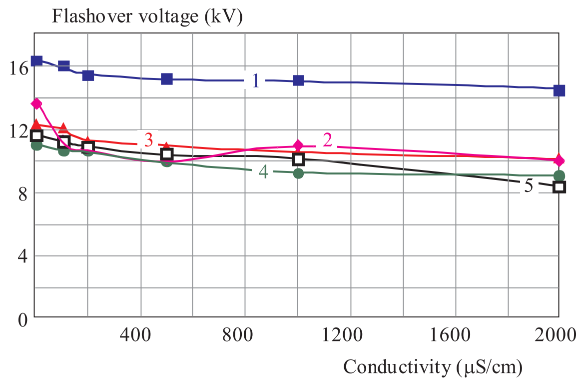


Fig. 14. Flashover voltages for various conductivities and positionings of the droplets. 1 rubber–(1), 2 rubber–(2A), 3 rubber–(2B), 4 rubber–(2C), 5 rubber–(5) (in all experiments droplets of 0.3 ml were used).

water droplet conductivity, polymer surface roughness, droplet volume and droplet positioning. These parameters affect the droplet behaviour. The increase of conductivity causes a decrease of flashover voltage and this is a conclusion generally valid, independently of the material used. The surface roughness influences in a positive way the flashover voltage when the number of droplets is large. The surface roughness hinders the oscillation of droplets and consequently these cannot create a conducting path. An increase in droplet volume causes a decrease of flashover voltage. This agrees with previous experimental observations with either *ac* or *dc* electric fields [17] as well as with observations reported in [18]. The position of droplets with respect to the electrodes is of importance. When the droplets are near the electrodes, then the flashover voltage decreases. From the above it is concluded that the material used plays a predominant role in determining the flashover voltage. Hydrophobic materials, such as silicone rubber, perform better than PVC and rubber.

This work needs, however, to be continued. More materials, such as EPDM, epoxy resin *etc*, should be tested. Work in the future should encompass measurements of contact angle before and after the experiment as well as study of droplets on polluted surfaces. Moreover, work should be carried out with polymeric surfaces which are aged. It would be interesting to see whether and how the present findings are applicable to surfaces having cracks (and consequently increased roughness) and are likely to absorb more water. Bearing also in mind the shape of real insulators, one should carry out research also on water droplets on polluted inclined surfaces. Furthermore, the same series of experiments should be repeated with very thin (∼ 1 mm) polymeric silicone rubber coatings and the droplet behaviour should be investigated in connection to the loss of hydrophobicity [19].

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