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A STUDY OF THE BEHAVIOUR OF WATER DROPLETS ON POLYMERIC SURFACES UNDER THE INFLUENCE OF ELECTRIC FIELDS IN AN INCLINED TEST ARRANGEMENT

Michael G. Danikas [*] — Pavlos Ramnalis [*] — Ramanujam Sarathi [**]

This paper investigates the influence of various parameters on the behaviour of water droplets on polymeric surfaces under electric fields. An inclined plane test was carried out to understand the droplet behaviour in strong electric field. Parameters, such as water droplet conductivity, droplet volume, polymeric surface roughness and droplet positioning with respect to the electrodes were studied. The flashover voltage is affected by all aforementioned parameters. The droplet positioning is in some cases more vital than the droplet volume.

Keywords: water droplet, polymeric surface, hydrophobicity, partial discharges, local arcs

1 INTRODUCTION

Water droplets on a polymeric surface may cause corona under the influence of an electric field and can cause deterioration to the insulation surface even in conditions of a low pollution level. Water droplets on a polymeric surface increase locally the applied electric field. Local field intensifications lead to partial discharges (PD) and/or localized arcs, which may render possibly dry bands on the polymeric surface. Local arcing will eventually bridge the dry bands and a complete flashover will finally ensue. 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 particular characteristics, namely that indoor insulation is stressed more and is subjected to a different type of environmental influences than outdoor insulation [1, 2]. A combination of water droplets and dust-like impurities on the surface of a polymeric surface may lead to a conducting contamination layer, which may cause a reduction of the flashover voltage. The design of high voltage insulators, they can be for indoor or outdoor use, one should take into account not only the pollution level, the insulator material and the appropriate voltage level, but also the influence of water droplets on the flashover voltage. Previous work, carried out in this laboratory, tackled the behaviour of water droplets for a wide range of water conductivities ($1.7\,\mu$S/cm–$10000\,\mu$S/cm) [3, 4]. In both publications it was shown that among the factors influencing the behaviour of the water droplets were the water conductivity, polymer surface roughness, droplet volume and droplet positioning with respect to the electrodes.

In the present work, a study of the aforementioned parameters on the water droplet behaviour under the influence of a uniform electric field in the range of 1.7μS/cm–$2000\,\mu$S/cm was carried out. All tests were performed with an inclined test arrangement, in order to simulate the behaviour of water droplets on the surface of a real insulator. The angle used with respect to the horizontal was 10°. Such an angle was chosen because of its immediacy to industrial insulators.

2 FORCE BALANCE AT THE DROPLET/POLYMER SURFACE INTERFACE

Modelling of a wet contaminated surface was given in other publications and only a brief outline is provided here [5]. Condensation of droplets on the surface of a high voltage insulator can come about from droplet germs. In Fig. 1, the forces exercised on the droplet are shown in the case, where no electrical field is applied. 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}). When an electric field is applied, the droplet deforms because of an additional force. The tangential electric field on the surface of the insulator creates a force on the surface of the droplet which causes its deformation. The deformation of the droplet affects the field distribution. Local field intensifications may result, which will cause micro-discharges between the droplets. This is the beginning of the chemical deterioration of the insulator surface.

Hydrophobicity may locally be lost. The voltage difference across the droplet will be diminished and micro-discharges will follow. Solvable nitrates, which are the result of the electrochemical deterioration, cause a higher conductivity of the water droplets. Dry zones may follow. It is important to bear in mind that not only the influence of the applied electric field on the shape of the droplet is of great significance, but also the influence of the disintegrated droplet on the electric field distribution [5, 6].

[*] Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece, mdanikas@ee.duth.gr,
[**] Department of Electrical Engineering, IIT Madras, Chennai-600 036, India

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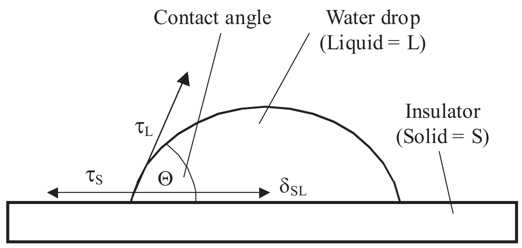

Fig. 1. Force balance at the solid/liquid interface at a water droplet on an insulating surface

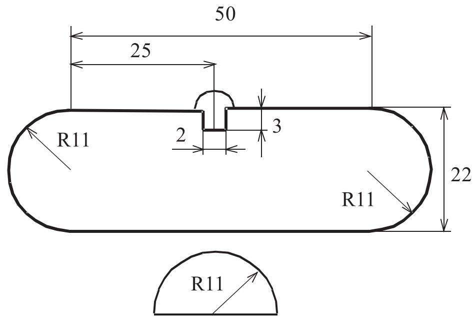

Fig. 2. Top view (above) and cross section (bottom) of the electrodes used (all dimensions in mm)

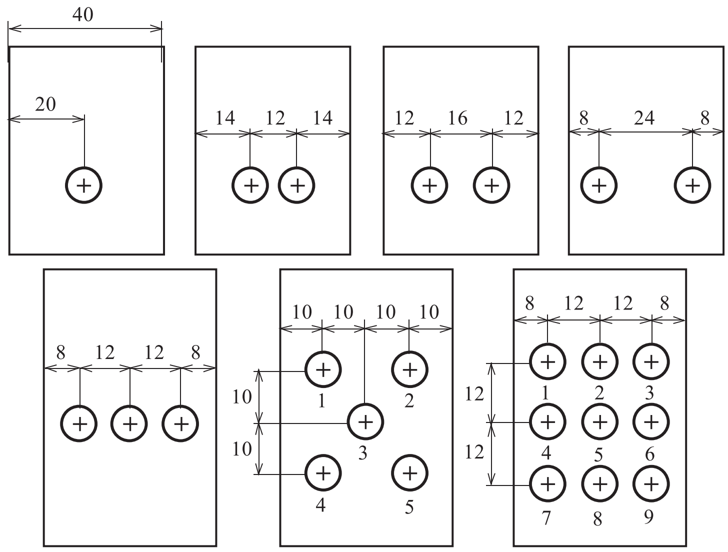

Fig. 3. Top view showing the droplet arrangements. Starting from top left, the arrangements were named as arrangement (1) (with one droplet), arrangement (2a) (with two droplets, 14-12-14), arrangement (2b) (with two droplets, 12-16-12), arrangement (2c) (two droplets, 8-24-8), arrangement (3) (with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

Hydrophobic polymeric surfaces are characterized by a low surface conductivity which in turn gives a low discharge activity and a higher flashover voltage. This holds also for polluted environments. Reduced hydrophobicity implies a higher risk for flashover of the insulator. Hydrophilic materials, on the other hand, are very sensitive to polluted environments, and are characterized by a significant activity of local discharges [7].

3 EXPERIMENTAL ARRANGEMENT AND PREPARATION OF THE SAMPLES

The aim of this paper is to study the behaviour of water droplets under the influence of an electric field. The voltage supplied was 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. Consequently, the applied voltages were accurate up to 24 kV). The electrodes used were of copper. A top view as well as a cross section of an electrode is shown in Fig. 2. The electrodes were half cylindrical in shape. Attention was paid to the smoothness of the electrode surfaces, so that no unnecessary field enhancements could be noticed.

The water droplets were 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 polymeric surface is given in [3]. The photograph of the inclined plane test is shown in Fig. 3. The polymeric materials used were PVC, rubber and silicone rubber. Surface roughness and resistivity of the material were measured. Surface roughness was measured using perthometer (Type Perthometer M4P) and the roughness was 0.25 μm for PVC, 0.79 m for silicone rubber and 1.10 μm for rubber. Resistance measurements of the material were performed with a Megger (BM25 type) and they gave a resistance of 206 GΩ for PVC, 3100 GΩ silicone rubber and 2660 GΩ for rubber. The above values of surface roughness and surface resistance were not isolated values, but each of them was the mean of three measurements [8, 9].

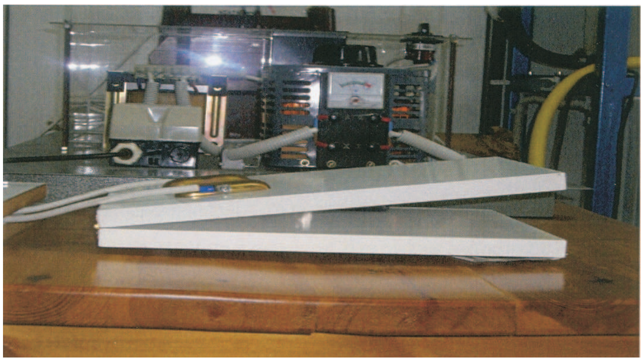

Fig. 4. The inclined plane test setup (side view)

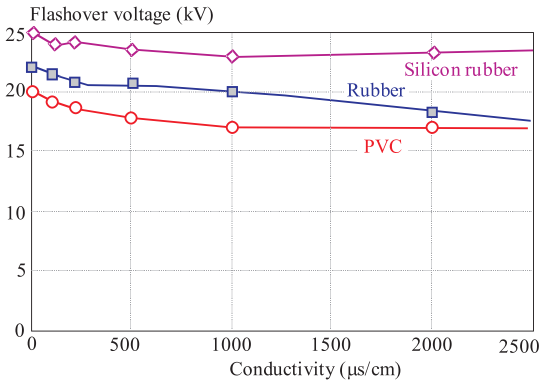

Fig. 5. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone Rubber. Droplet arrangement (1)

In the present work, by mixing a known quantity of NaCl in distilled water forming solutions with conductivity in the range 1.7 μS/cm to 2000 μS/cm were used as droplets. The range of conductivity were chosen based on the conductivity of natural rain and its values lie in the range 50–150 μS/cm, whereas the tests with porcelain and glass insulators are performed with conductivities of 2500 μS/cm [10].

4 EXPERIMENTAL PROCEDURE

The materials used were PVC, silicone rubber and rubber. Various droplet arrangements were studied. These arrangements are given in Fig. 4. Each droplet had a volume of 0.2 ml. The electrodes were positioned at a distance of 4 cm from each other. The parameters investigated were the water conductivity, the roughness of the insulating surface, the positioning of the droplets and their volume. The insulating surfaces were used as they were received from the manufacturer without any further treatment. After putting the droplets on the polymeric 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 again up to the previous flashover value minus 1.2 kV, so that no new flashover would occur. At this voltage the arrangement would stay for 1 min. If no flashover occurred, the voltage was raised by 0.4 kV and the procedure was repeated until flashover occurred. The reason we left every time the voltage on for 1 min was to give a necessary time interval for the droplet(s) to deform and for the partial discharge to initiate.

It should be noted that there is observed a tendency for the droplets to slide, especially for PVC because of its smooth surface. The droplet slide was minimal in the case of rubber, which was the roughest of the three materials used. Elongation of the droplets was observed as the applied voltage was larger. A more evident oscillation of the droplet was observed with silicone rubber. The reason for that was because the aforementioned material is more hydrophobic than the other two. Consequently, the droplet, for a defined droplet volume, has a smaller contact area with silicone rubber, and for this reason it oscillates more [8]. In some cases, such as with PVC with a droplet conductivity of 1.7 μS/cm and with the arrangement (1) of Fig. 3, ejection of minute charged droplets was observed just before flashover [11].

5 EXPERIMENTAL RESULTS

At first, experiments were performed without any droplets between the electrodes. This was done in order to have reference values of the flashover voltage and also to understand the influence of the number of droplets between the electrodes on reducing the flashover voltage. The flashover voltages without any droplets measured were 23 kV ($\pm$0.5) for PVC, 25 kV ($\pm$0.5) for silicone rubber and 24 kV ($\pm$0.5) for rubber. The flashover voltages of the three materials used were very similar.

In Figs. 5–11 the variation of flashover voltage with respect to the droplet conductivity for different droplet arrangements is shown. It is evident that silicone rubber presents a higher flashover voltage than the other two materials. It should be noted, however, that in the case of droplet arrangements (5) and (9) rubber seems to be as good as silicone rubber. A possible explanation might be that in such a case the droplets cover a significant part of the polymeric surface and hence they play an even more important role than the polymer itself. This in combination with the fact that the rubber has a rougher surface compared to the other two materials, it exhibits lesser oscillation.

The better performance of silicone rubber is due to its hydrophobicity [5, 12]. The contact angle being larger, the droplets have a minimum contact with the insulation material as in the case of silicone rubber. Figs. 12–14 show the influence of droplet volume on the flashover voltage. It is clear that the number of droplets affects the flashover voltage, *ie* the larger the number, the lesser the flashover voltage. An exception to that we have with the arrangement of 3 and 5 droplets. It is evident that larger flashover voltages were observed with 5 droplets than with 3 droplets. A possible explanation of that is that in the case of 3 droplets, the distance between electrode and

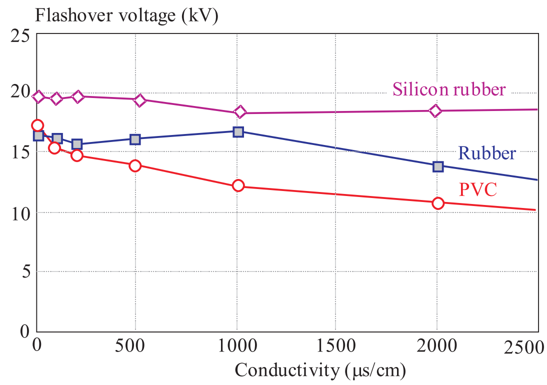

Fig. 6. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone rubber. Droplet arrangement (2a)

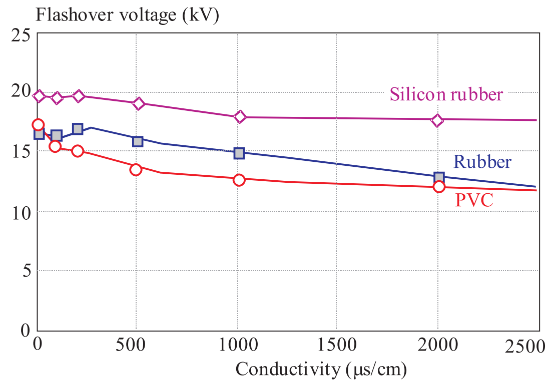

Fig. 7. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone rubber. Droplet arrangement (2b)

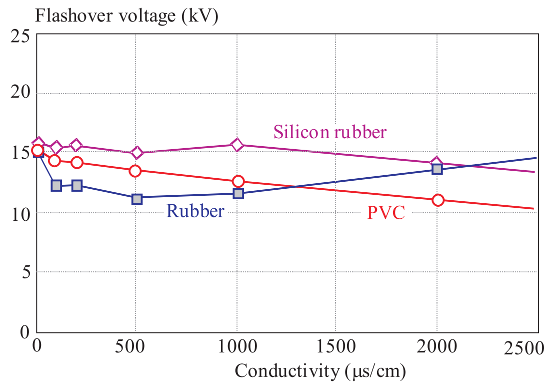

Fig. 8. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone rubber. Droplet arrangement (2c)

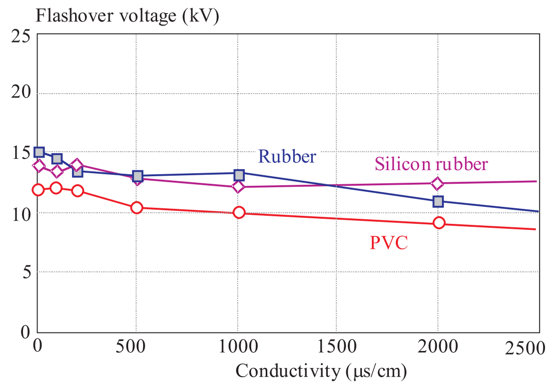

Fig. 9. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone rubber. Droplet arrangement (3)

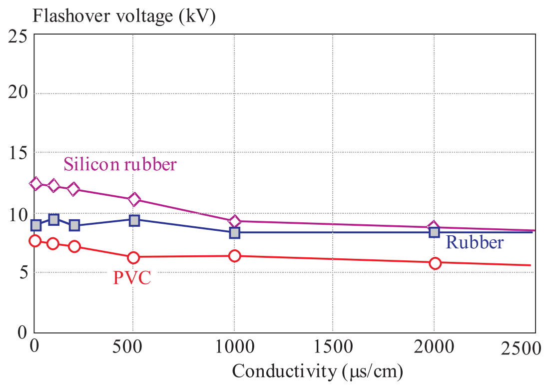

Fig. 10. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 silicone rubber. Droplet arrangement (5)

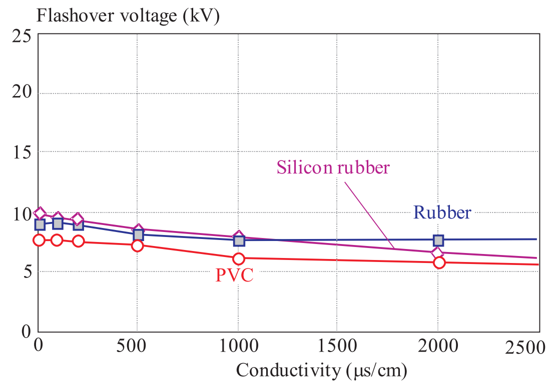

Fig. 11. Flashover voltage for various conductivities: 1 – PVC, 2 – rubber, 3 – silicone rubber. Droplet arrangement (9)

droplet is smaller than in the case of 5 droplets. Consequently, one might say that there are occasions where the positioning of the droplets with respect to the electrodes which plays a more vital role than the whole droplet volume. A further validation of the above consists in the comparison of the flashover voltages in the cases of 3 and 9 droplets. It is observed that the flashover voltages for both these arrangements are not that different although the droplet volume triples.

An interesting case consist also the droplets arrangements 2a, 2b and 2c. Higher values for flashover voltage were observed for arrangement 2a, then for arrangement 2b and the lower flashover voltage was observed for droplet arrangement 2c. This fact reinforces the above observations, namely that the positioning of the droplets play a crucial role, *ie* the closer the droplets to the electrodes, the lower the flashover voltage. It is to be noted that similar observations were made also in [3, 4], where not an inclined arrangement was used but a horizontal one. What is presented in this paper is an approach of the behaviour of water droplets on polymeric surfaces with an inclined electrode arrangement. The results were repro-

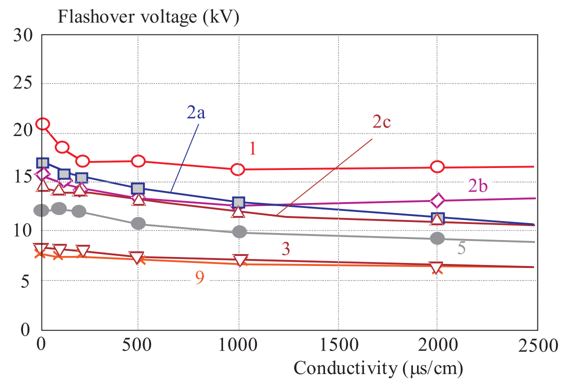

Fig. 12. Flashover voltage for various conductivities, positioning and volume of the droplets. PVC used. 1 – arrangement (1), 2 – arrangement (2a), 3 – arrangement (2b), 4 – arrangement (2c), 5 – arrangement (3), 6 – arrangement (5), 7 – arrangement (9).

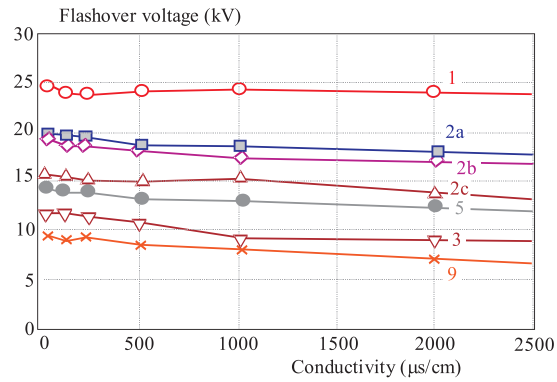

Fig. 13. Flashover voltage for various conductivities, positioning and volume of the droplets. Silicone rubber used. 1 – arrangement (1), 2 – arrangement (2a), 3 arrangement (2b), 4 – arrangement (2c), 5 – arrangement (3), 6 – arrangement (5), 7 – arrangement (9).

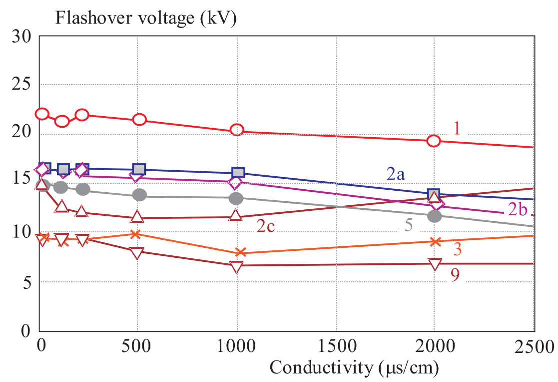

Fig. 14. Flashover voltage for various conductivities, positioning and volume of the droplets. Rubber used. 1 – arrangement (1), 2 – arrangement (2a), 3 – arrangement (2b), 4 – arrangement (2c), 5 – arrangement (3), 6 – arrangement (5), 7 – arrangement (9).

ducible but not that many tests were carried out which would allow a statistical study of the collected data. The main interest of this paper concentrates on the study of the behaviour of the droplets. In the present context, no emphasis was given to the quantification of the studied parameters.

6 DISCUSSION

In this paper, some parameters influencing the droplet behaviour on polymeric surfaces were investigated, such as water conductivity, droplet volume, polymeric surface roughness and droplet positioning. An increase of conductivity causes a decrease of flashover voltage. This is a statement valid irrespective of the polymer used. The surface roughness affects in a positive way the flashover voltage, when the number of droplets is large. The surface roughness functions as a hindrance to the movement of the droplets, and consequently renders their oscillation more difficult. An increase of droplet volume causes a decrease of flashover voltage. This is in agreement with experimental observations published before with either ac or dc electric fields [13]. The position of the droplets with respect to the electrodes is of vital importance. With the droplets nearer the electrodes, the flashover voltage decreases. This is a phenomenon observed, albeit in different circumstances and conditions, also with enclosed cavities in solid dielectrics, where discharges become much more intense when one of the enclosing walls is an electrode [14].

The above show clearly that the polymeric material plays a predominant role in determining the flashover voltage and the behaviour of water droplets. Hydrophobic materials, such as silicone rubber, perform better than PVC or rubber. With this in mind, one should also note that most polymeric materials for outdoor applications present some sort of hydrophobicity. However, the advantage of silicone rubber consists in the fact that it does not only have this property, it can also regenerate it [15].

The forming of water paths, between the droplets as well as between the droplets and the electrodes, generally follow the direction of the applied electric field. The general activity in the form of discharges and droplet movement with rougher surfaces, sets in at higher voltages. In the case of just one droplet, with the application of the field, a deformation starts turning later to instability. Such behaviour was observed with the inclined arrangement as well as with previous horizontal arrangements [3, 4]. Also in the case of the inclined arrangement, the role of the 'triple points' (*ie* the points where air, polymeric surface and droplet meet each other) is vital. The forces exercised on the droplets, because of the applied electric field, are quite strong, and therefore, the 'triple points' move towards the electrodes. Experimental data published recently, validate what is reported here [16]. Such movement of 'triple points' causes the spread of the droplets. The spread of droplets is perhaps the most characteristic phenomenon observed with the inclined electrode arrangement. It is not, however, the only one observed. Droplet oscillation, formation of water paths, collapsing of two droplets into a larger one, ejection of small charged droplets from a larger one, were also noted during the experiments. In this respect, the present work offers similar conclusions with those in [3, 4, 8, 9, 16, 17].

It is to be noted that the inclined electrode arrangement, used here, should not be compared by any means with the well known arrangement of the inclined plane test [18]. In the latter, a film of electrolyte is arranged to trickle down the back surface of a sheet and the samples are rated in terms of the voltage which causes a track to form in one hour [19]. In other words, the inclined plane test is a means of evaluating resistance to tracking and erosion of insulating materials for outdoor use, whereas the inclined electrode arrangement used in this work is a setup to study some parameters affecting the droplet movement on polymeric materials. The inclined plane test is an accelerating test [18]. The angle which was used in our experiments, *ie* the angle of 10°, was taken from real insulators. The purpose was to see the droplet behaviour under an electric field in, as much as possible, real conditions. The present work confirms some general tendencies noted in [3, 4].

7 CONCLUSIONS

Water droplet conductivity, polymer surface roughness, droplet volume and the positioning of droplets with respect to the electrodes constitute important parameters affecting the behaviour of droplets under the influence of an electric field with an inclined plane electrode arrangement. Increased conductivity, smoother polymer surfaces and increased droplet volume cause a reduction of the flashover voltage. The droplet positioning with respect to the electrodes plays a vital role in reducing the flashover voltage and, on occasions, is more important than the droplet volume.

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Michail G. Danikas, born in 1957, Kavala, Greece, received his BSc and MSc degrees from the University of Newcastle-upon-Tyne (England), in electrical and electronic engineering, and his PhD Degree from Queen Mary College, University of London England, in 1980, 1982 and 1985 respectively. From 1993 he has been with Democritus University of Thrace, Department of Electrical and Computer Engineering, since 1998 as Associate Professor. His current research interests are breakdown in transformer oil, simulation of electrical tree propagation in polymers, study of partial discharge mechanisms in enclosed cavities, magnitude and surface phenomena in indoor and outdoor high voltage insulators.

Pavlos Ramnalis studied at Democritus University of Thrace, Department of Electrical and Computer Engineering, and received his Diploma in 2006. He is currently pursuing postgraduate studies in the same department.

Ramanujam Sarathi is currently an Associate Professor and Head in charge of High voltage Laboratory, in the Department of Electrical Engineering, Indian Institute of Technology, Madras. He obtained his PhD from the Indian Institute of Science, Bangalore in 1994. post-doctoral work at the Akita University. His major area of specialisations is outdoor insulation, treeing studies, and Condition Monitoring of Power apparatus. He is member of IEEE.