Journal of ELECTRICAL ENGINEERING, VOL. 57, NO. 3, 2006, 130–137

STUDY OF PARAMETERS RELATED TO DETERIORATION PHENOMENA DUE TO WATER DROPLETS ON POLYMERIC SURFACES

Michael G. Danikas —
Paschalis Rakitzis — Konstantinos Karakoulidis *

In this publication 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, rubber and ethylene propylene rubber (EPR) were used for the experimental work. The deterioration phenomena — due to partial discharges (PD) and localized arcs — were studied in terms of very high water conductivity (extreme pollution), polymer surface roughness, droplet volume and droplet position *wrt* the electrodes. All four mentioned parameters affect the flashover voltage. A comparison between the aforementioned materials *wrt* droplet behaviour was made and discussed. Proposals for future research are also put forward.

Keywords: water droplets, polymeric surfaces, uniform field, outdoor insulation, indoor insulation, pollution

1 INTRODUCTION

Water droplets on the surface of a polymeric insulator may cause — under an 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 which in turn render possible the 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 more or less for both outdoor and indoor insulation although each of the aforementioned categories has its own peculiarities, namely that indoor applications are stressed more and are subjected to a different type of environmental influences [1, 2]. 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. Designing high voltage insulators (for both indoor and outdoor use) requires that care should be taken not only to the pollution level, the insulator material and the voltage level but also to the influence of water droplets on the flashover voltage. In a previous paper [3], results were given regarding PVC, silicone rubber and rubber for water conductivities in the range $1.72000\,\mu$S/cm. In [3], it was shown that water droplet conductivity, polymer surface roughness, droplet volume and droplet positioning affect the droplet behaviour.

In the context of the present paper, a study of the aforementioned parameters on the water droplet behaviour under the influence of a uniform electric field was carried out. In the present paper, water droplet behaviour was examined under heavy pollution, with water conductivities ranging from 2500 up to $10000\,\mu$S/cm on the surfaces of polymeric materials such as PVC, rubber, silicone rubber and ethylene propylene rubber (EPR). These materials present various degrees of roughness, resistivity and hydrophobicity. The aim of this paper is to collect — and possibly explain — data on the above far end of the pollution scale. What distinguishes the present paper from an already published previous work of ours [3], is that in the earlier paper another range of water conductivities was investigated and also fewer polymeric materials.

2 FORCE BALANCE AT THE DROPLET/POLYMER SURFACE INTERFACE

A modelling of a wet contaminated surface has already been given in other publications and it will not be repeated here [3, 4]. Condensation of droplets on the surface of an HV insulator can come about from droplet germs. In Fig. 1, the forces exercized on the droplet are shown in case that no applied electric field exists [4]. Such forces are the surface tension of the liquid (τ_L), the surface tension of the solid (τ_S) and the interfacial tension between liquid and solid (δ_{SL}). When an electric field is applied, the droplet will deform 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 influences the field distribution. Local field enhancements may result and these in turn will cause micro-discharges between the droplets. This is the beginning of the electrochemical deterioration of the insulator surface. Hydropho-

---

* Democritus University of Thrace, Department of Electrical and Computer Engineering, Electric Energy Systems Laboratory, 67100 Xanthi, Greece

ISSN 1335-3632 © 2006 FEI STU

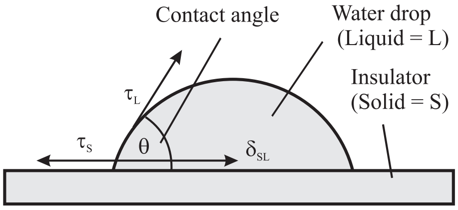

Fig. 1. Force balance at the interface solid/liquid at a water droplet on an insulating surface

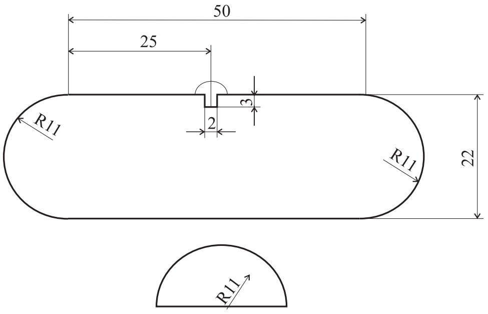

Fig. 2. Top view (above) and cross section (bottom) of the electrodes used (all dimensions in mm)

bicity may locally be lost. The voltage difference across the droplet — which has a decreased resistivity — will be diminished and micro-discharges will ensue. Because of the electrochemical deterioration which sets in, solvable nitrates resulting in a higher conductivity of the water droplets are created. The well known dry zones may follow [4]. It is to be noted that it is not only the influence of applied the electric field on the shape of the droplet that counts, but also the influence of the disintegrated droplet on the electric field distribution [4].

Hydrophobic polymeric surfaces are characterized by a low surface conductivity which in turn gives a low discharge activity and a higher flashover voltage, especially in a polluted environment. Reduced hydrophobicity implies a higher risk for flashover. The classification of hydrophobic and hydrophilic surfaces has been proposed in studies from the Swedish Transmission Research Institute (STRI) [5, 6]. These two publications [5, 6] provide an easy to use and convenient in field method for evaluation of the insulator wettability, also in the case in which such an insulator has heterogeneous wetting properties (*ie* when a minor part of it is hydrophobic).

3 EXPERIMENTAL ARRANGEMENT AND PREPARATION

The aim 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 the measurement. In this way, we may consider that the applied voltages are accurate up to 24 kV. This value was not superseded during the whole series of the experiments). The electrodes used had a top view shown in Fig. 2 (top) and a cross section also in Fig. 2 (bottom). All dimensions appearing in Fig. 2 are in mm. They were made of copper and they had a half cylindrical shape with 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 [7]. Fig. 3 shows the droplet arrangements used in this work. The polymeric materials used were PVC, silicone rubber, rubber and EPR. Measurements of surface roughness and of resistivity were performed with the above mentioned materials. Measurements of surface roughness are concerned with measurements of surface asperities which have heights in the range of 0.3 400 μm. Measurements of 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, 1.10 μm for rubber and 1.13 μm for EPR. Measurements of 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, 2660 GΩ for rubber and 550 GΩ for EPR. The above given values of both roughness and resistivity were not isolated values, but each of them was the mean of three measurements [7]. 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 2500, 3500, 5000 and 10000 μS/cm for the droplets were used, significantly higher than the ones employed in [3]. 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. Four samples with water conductivities as mentioned above were prepared [7]. What differentiates the present work from [3], is that now we have additionally EPR to test and water conductivities higher than those of [3]. The reason why we chose such high water conductivities is given below in Section 6. The reference [3] and the present work have certainly common points but they also differ to a significant extent.

4 THE EXPERIMENTAL PROCEDURE

The experimental procedure is essentially the same with that described in [3]. 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

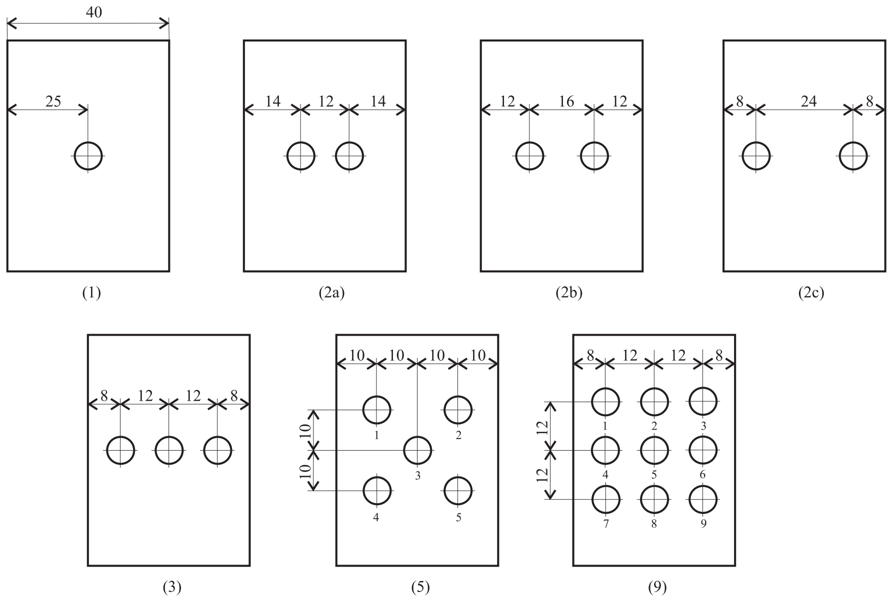

Fig. 3. Top view showing the droplet arrangements. Starting from top left, the arrangements were named as arrangement (1) (with one droplet), arrangement (2A) (with two droplets, 14-12-14), arrangement (2B) (12-16-12), arrangement (2C) (8-24-8), arrangement (3) (with 3 droplets), arrangement (5) (with 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.

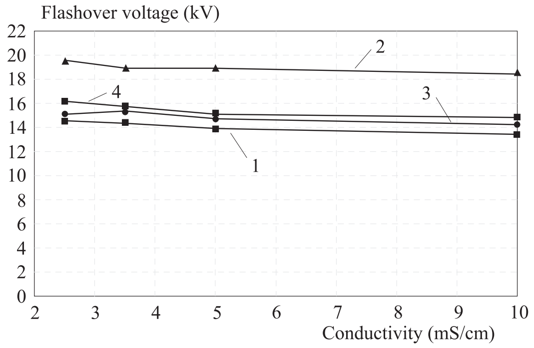

Fig. 4. Flashover voltage for various conductivities. Droplet volume 0.3 ml, 1 - PVC (1), 2 - silicone rubber (1), 3 - rubber (1) and 4 - EPR (1).

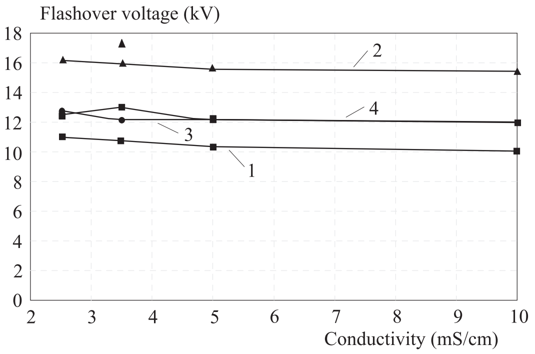

Fig. 5. Flashover voltage for various conductivities. Droplet volume 0.2 ml, 1 - PVC (2B), 2 - silicone rubber (2B), 3 - rubber (2B) and 4 - EPR (2B).

droplet volumes were 0.2 and 0.3 ml. Such volumes were chosen in order to better simulate 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 roughness of the insulating surface. The insulating surface was not treated in any way but it was used as it was received from the manufacturer. No information about the exact chemical composition of each of the insulating surfaces used was offered by the manufacturer. After putting the droplets on the surface, the voltage was slowly raised until flashover occurred. After that and after cleaning the surface and after putting new droplets on it, the voltage was raised 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 flashover occurred, the voltage was raised by 0.4 kV and the procedure is repeated until flashover occurred. This was the flashover 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. What is presented here is a first approach to the behaviour of water droplets on polymeric surfaces under the influence of an electric field. Although the results of the tests were reproducible, not many repeated tests were carried out and consequently, a statistical treatment of the collected data was not possible. It is to be emphasized that, in this paper, our main interest at this stage is a qualitative approach, not a quantitative one. The main aim of this work was the study of the behaviour of the water droplets on polymeric surfaces and the relevant parameters affecting this behaviour, not the quantification of these parameters, a task to be performed at later stage.

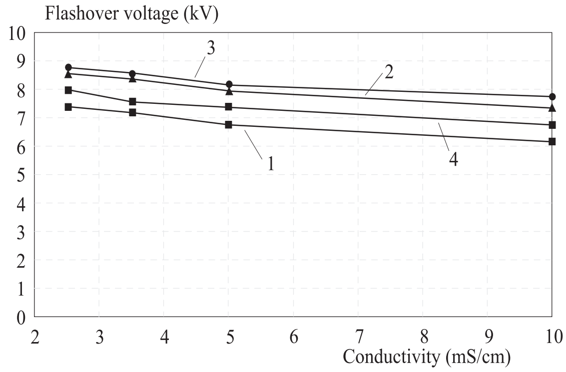

Fig. 6. Flashover voltage for various conductivities. Droplet volume 0.3 ml, 1 - PVC (5), 2 - silicone rubber (5), 3 - rubber (5) and 4 - EPR (5).

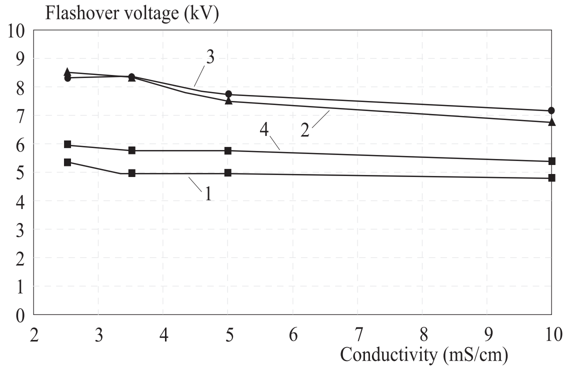

Fig. 7. Flashover voltage for various conductivities. Droplet volume 0.2 ml, 1 - PVC (9), 2 - silicone rubber (9), 3 - rubber (9) and 4 - EPR (9).

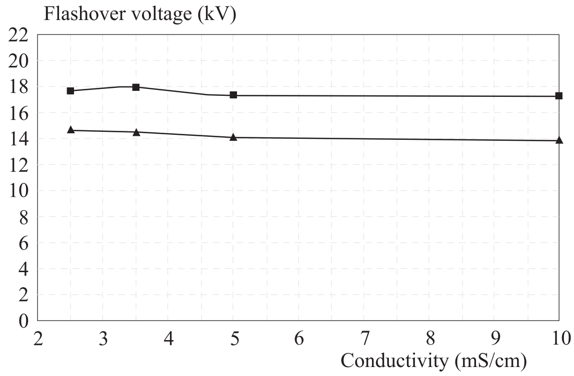

Fig. 8. Flashover voltage for various conductivities. Triangles refer to PVC with one droplet of 0.3 ml, squares refer to PVC with one droplet of 0.2 ml.

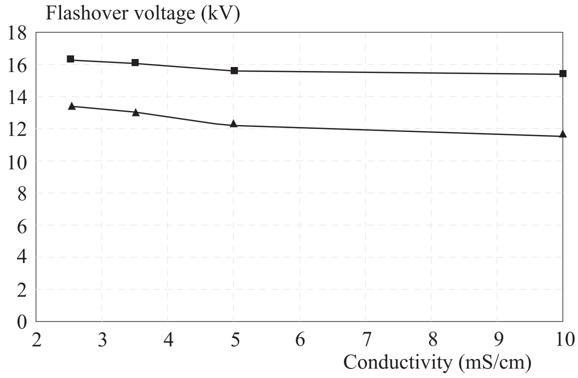

Fig. 9. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (silicone rubber used, droplet arrangement 2B).

5 EXPERIMENTAL RESULTS AND SOME ADDITIONAL COMMENTS

At first, experiments were performed without any droplets between the electrodes. This was done in order to have some flashover 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), 24 kV (±0.5) and 23 (±0.5) for PVC, silicone rubber, rubber and EPR respectively. We realize that the flashover values of the four materials were very similar. As we will realize later, the mentioned flashover values are at least 20 % higher than the flashover values with any sort of droplet arrangement and any kind of material. This proves that even the presence of a single droplet affects the flashover voltage.

At the first stage of this work the polymeric surfaces were subjected to the combined effect of electric stress and water droplets. When a single droplet is put between the electrodes, at first it oscillates and then elongates under the effect of the electric field. The droplet oscillation depends on the roughness of the surface and it is more pronounced in the case of silicone rubber. This may happen because of the greater hydrophobicity of silicone rubber. In this case, the contact surface of a single droplet is smaller than with polymers of less hydrophobicity (however, one might say that the droplet oscillation is not exclusively a matter of the contact angle because of the hydrophobicity but it also depends on the surface roughness. Droplet oscillation is most probably the result of the interplay of these two factors). As the number of droplets increases, the droplets oscillate more. Water paths between the droplets are created which may endure even after the removal of the applied field. Droplet oscillation is more intense on the less rough surfaces. (The figures shown in this paper refer to a significant part of the experimental work performed. For the sake of brevity, not all experimental results can be shown in the context of the paper. Full details are given in [7]).

Figs. 4–7 show the graphs of some droplet arrangements. It is obvious that the droplet conductivity affects the flashover voltage [8]. Generally, silicone rubber performed better than the other three materials. In the arrangements with 5 and 9 droplets, however, silicone rubber was marginally worse than rubber. In other words, silicone rubber performs not that well when the total droplet volume is between 15 ml and 18 ml. Why this is so is not yet clear since the explanation of the role of the surface roughness (being greater with rubber and EPR

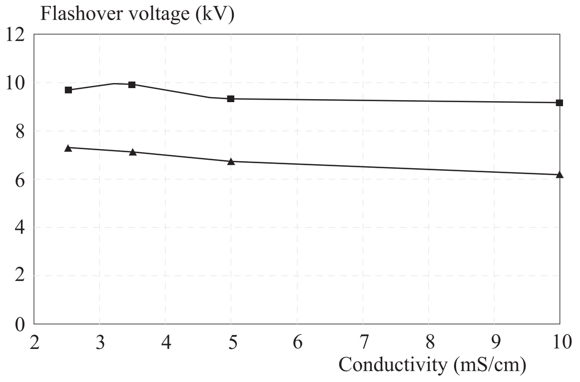

Fig. 10. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (PVC used, 5 droplets).

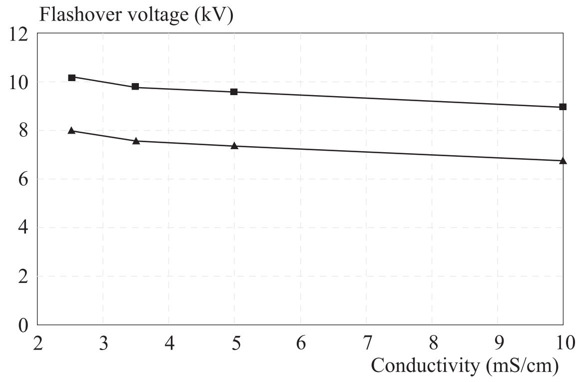

Fig. 11. Flashover voltages for various conductivities. Triangles symbolize droplets of 0.3 ml each and squares droplets of 0.2 ml each (EPR used, 5 droplets).

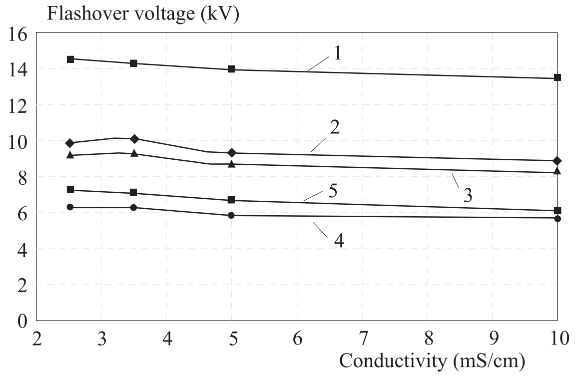

Fig. 12. Flashover voltages for various conductivities and positionings of the droplets. 1 PVC-(1), 2 PVC - (2A), 3 PVC-(2B), 4 PVC-(2C), 5 PVC-(5) (in all experiments droplets of 0.3 ml were used).

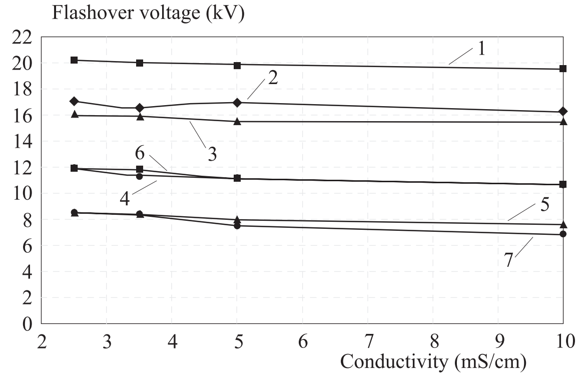

Fig. 13. Flashover voltages for various conductivities and positionings of the droplets. 1 SiR-(1), 2 SiR-(2A), 3 SiR-(2B), 4 SiR-(2C), 5 SiR-(3), 6 SiR-(5), 7 SiR-(9) (in all experiments droplets of 0.2 ml were used, SiR means silicone rubber).

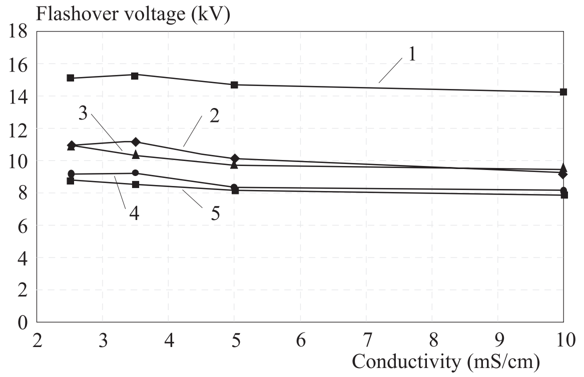

Fig. 14. Flashover voltages for various conductivities and positioning of the droplets. 1 rubber-(1), 2 rubber-(2A), 3 rubber-(2B), 4 rubber-(2C), 5 rubber-(5) (in all experiments droplets of 0.3 ml were used).

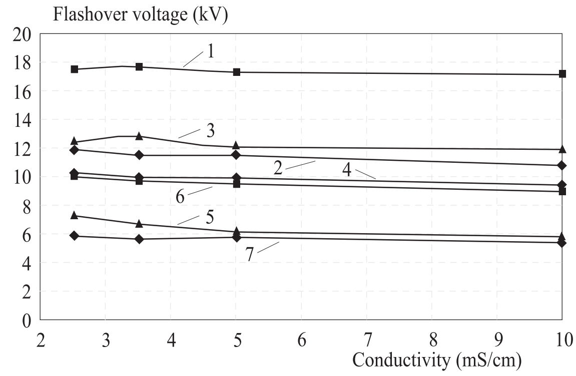

Fig. 15. Flashover voltages for various conductivities and positioning of the droplets. 1 EPR-(1), 2 EPR-(2A), 3 EPR-(2B), 4 EPR-(2C), 5 EPR-(3), 6 EPR-(5), 7 rubber-(9) (in all experiments droplets of 0.2 ml were used).

and lesser with silicone rubber) does not seem to work. The reason for that is that the EPR — being rougher than silicone rubber — presents worse results with 5 and 9 droplets. An explanation would probably take into account that in the present work we deal with really very high conductivities, much higher than in [3]. Silicone rubber though, gives, in general, better results as was also noted in other publications [9]. This may be due to its inherent hydrophobicity which renders the droplets on its surface having rather large contact angles.

Figs. 8–11 are indicative of the influence of droplet volume on the flashover voltage. The increase of droplet volume implies 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 [3, 10]. It is to be remarked that the influence of the droplet volume is, as expected, somehow more pronounced as the number of droplets increases (see, for example, Figs. 10 and 11). Figs. 12–15 show the influence of positioning of the droplets *wrt* the electrodes. From these figures, it is evident that the remarks made in [3], namely that the positioning of the droplets *wrt* the electrodes and not necessarily the droplet volume is what matters, are also valid here where we have very high water conductivities. The droplet arrangement 2C seems to have a rather low flashover voltage, *ie* the electrodes play a determining role for the flashover voltage since, as the droplets are near the electrodes, the electron emission and/or the electric field applied provoke much more intense phenomena. The higher electric field is related to the so called “triple points”, *ie*, to those common points where the electrode, the polymeric surface and the water droplet meet each other.

6 DISCUSSON

Some parameters influencing the behaviour of the water droplets on polymeric surfaces were discussed, namely, water droplet conductivity, polymer surface roughness, droplet volume and droplet positioning. The increase of conductivity causes a decrease of flashover voltage and this is a conclusion generally valid, independently of the material used. This holds true also for the very high conductivities investigated in this work. 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 easily 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 [11] as well as with observations reported in [12–14]. The position of droplets *wrt* the electrodes is of great 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, rubber or EPR. Having said that, it should be noted that most of the polymeric materials used for outdoor applications (or even indoor applications) present some sort of hydrophobicity. The advantage of silicone rubber is that it not only has this property, but it can also regenerate it [15, 16].

The forming of water paths, between the droplets as well as between the droplets and the electrodes, follows the direction of the applied electric field (Figs. 16, 17). The general activity — in the form of discharges and droplet movement — with rougher surfaces, sets in at higher voltages [17]. When there is only one droplet between the electrodes, the application of electric field results in its deformation which in turn leads to instability, in the sense of Fig. 18. The droplet deformation is reminiscent of similar phenomena taking place with a gas bubble in an insulating liquid, where the bubble assumes the shape of a prolate spheroid elongating until a critical shape is reached [18]. As said before, water droplets coalesce, elongate and extend, and this is due to the electric field developed at the “triple point”. It has been shown elsewhere that the maximum horizontal E-field at the “triple point” increases remarkably [19]. Furthermore, the forces exercised on the droplets, because of the applied electric field, are quite strong. Therefore, the “triple points” move towards both electrodes. Such observations agree with experimental data published in [20]. Needless to say that the description of droplet movement on a polymeric surface under an electric field is rather complex because, not only the aforementioned parameters should be taken into account (*ie* conductivity, droplet volume, droplet positioning and surface roughness), but also factors such as droplet height, contact angle and droplet spread on the surface. An effort for droplet simulation, with a computer programme being made elsewhere [20], does not take into account parameters like water conductivity and positioning *wrt* the electrodes. An objection to the present work would be that the authors used very high water conductivities in order to carry out their experiments. To this, one might reply that it is useful to have information on the behaviour of polymeric surfaces and water droplets even under extreme conditions. It should be noted, however, that experiments with very high conductivities were reported before, *eg* in [21]. In that particular work, conductivities up to $22000\,\mu$S/cm were investigated with high conductivity fog tests. The experiments reported here are not by any means standard laboratory tests. In the present paper the aim was to see droplet behaviour under very heavy pollution and finally to have, considering also the data of [3], information on the behaviour of polymeric surfaces with droplets for a wide range of water conductivities.

7 PROPOSALS FOR FUTURE RESEARCH

Future research should be directed towards a relation between droplet behaviour on an aged polymeric surface and leakage current. Given that the critical electric field at which an uncharged water droplet in a uniform electric field becomes unstable is

$$A_{cr} = c\sqrt{\gamma}/\varepsilon_0 r \tag{1}$$

where, γ the surface tension, r the droplet radius and c a constant, the aim will be to compare our experimental results — regarding the variation of the critical electric field with droplet radius — with those published elsewhere [10, 12–14, 22], as well as with the theoretical predictions of Eq. (1). One might say that in some of

Fig. 16. Arrangement with two droplet (2C). Silicone rubber used, droplet volume 0.2 ml each, conductivity 2500 μS/cm.

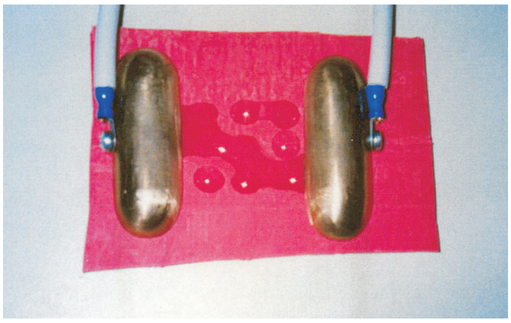

Fig. 17. Arrangement with five droplets (5). Silicone rubber used, droplet volume 0.2 ml each, conductivity 3500 μS/cm.

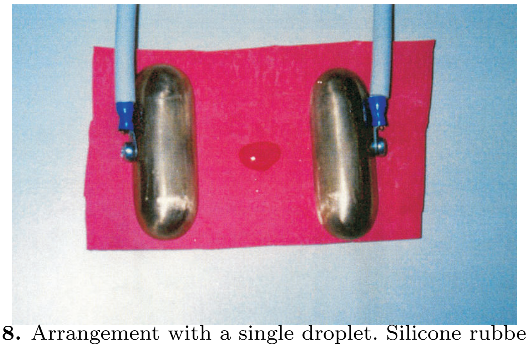

Fig. 18. Arrangement with a single droplet. Silicone rubber used, droplet volume 0.3 ml, conductivity 2500 μS/cm.

the aforementioned references, the water droplets investigated were not put on a polymeric surface, but it is known that water droplets on polymeric surfaces behave similarly to those in free space [10]. Droplet data collection continues [23], and such comparisons will be reported. In [23] for example, the droplet electrical behaviour was investigated with droplet volumes of 0.1 ml, whereas in [3] as well as in this paper the droplet volumes were 0.2 ml and 0.3 ml.

An effort should be made to relate aged surface damage with leakage current. How droplet movement and the relevant parameters influence an already aged surface? How such a surface is affected by this movement? Is there a relation between leakage current and consequent degradation? How do hydrophobic polymeric materials of behave under light and/or heavy pollution? Suggestions regarding part of the above questions have been put forward recently [24], namely that, polymer materials with the lowest leakage currents exhibit the least degradation whereas those with the highest currents were seen to suffer the greatest damage. Nevertheless, more work is needed in order to clarify certain points in relation to water droplets and especially the interplay between them and an aged polymeric surface. Which are, for example, the factors affecting droplet behaviour on an aged polymeric surface subjected to a multitude of stresses? What is the role of surface cracks in the case of a hydrophobic aged surface, always in relation to the droplet behaviour? Do they contribute to the worsening of the surface or do they — at the same time — improve the coming to the surface of the low molecular weight (LMW) substances, which regenerate hydrophobicity? These are some questions in great need of an answer. Long-term tests are also needed in order to see the link between the hydrophobicity loss of some polymers with water droplet induced discharges. It has been indicated already that, even under normal moisture conditions, such discharges become an important long-term ageing factor [25]. Moreover, the aforementioned positioning of water droplets and its role has to further investigated, especially in connection to recent findings suggesting that control of the electric field near the end-fittings of insulators may smoothen the electric field distribution due to water droplet low-energy discharges [26]. The effect of the number of droplets on the flashover voltage as well as the distortion of the electric field distribution by the number of the droplets has also to be examined since there are indications — from field computations — that the electric field near the “triple point” (or triple junction) is about 2 to 4 times the original value [4, 26].

8 CONCLUSIONS

This work shows that various parameters affect the electrical behaviour of water droplets on polymeric insulating surfaces. The water conductivity in all experiments was rather high. All four parameters (water conductivity, droplet volume, droplet positioning and polymer surface roughness) affect the flashover voltage although the degree of the importance of each of them varies. One of the significant points of this work is that the positioning of the droplets plays a greater role in determining the flashover voltage than the droplet volume.

Acknowledgements

The authors thank the anonymous referees for their useful comments which greatly contributed in improving the present paper.

REFERENCES

[1] KIND, D.—KAERNER, H. : High Voltage Insulation Technology, Eds. Vieweg, Braunschweig, 1985.

[2] DANIKAS, M. G.: Surface Phenomena on Resin-type Insulators under Different Electrical and Non-electrical Stresses in the Early Stage of Ageing, Facta Univers. **13** (2000), 335-352.

[3] KARAKOULIDIS, K.—DANIKAS, M. G.—RAKITZIS, P.: Deterioration Phenomena on Insulating Surfaces due to Water Droplets, J. Electr. Eng. **56** No. 7-8 (2005), 169-175.

[4] KLOES, H.-J.—KOENIG, D.—DANIKAS, M. G.: Electrical Surface Discharges on Wet Polymer Surfaces, Proc. 8th Int. Symp. Gas. Diel., June 2-5, 1998, Virginia Beach, Virginia, USA, 489-495.

[5] STRI Guide 92/1, "Hydrophobicity Classification Guid", 1992.

[6] ERIKKSON, A.—WIKSTROEM, D.: Influence of the Hydrophobicity of Outdoor Insulators on the Flashover Voltage, Proc. Nordic Insul. Symp. (NORD-IS), June 13–15, 1994, Vaasa, Finland, 39-51.

[7] RAKITZIS, P.: Flashover Pheomena on Polymeric Surfaces Under the Influence of a Uniform Electric Field, MSc Thesis, Democritus University of Thrace, Department of Electrical and Computer Engineering, Xanthi, 2003 (in Greek).

[8] KEIM, S.—KOENIG, D.: Study of the Behaviour of Droplets on Polymeric Surfaces under the Influence of an Applied Electrical Field, Ann. Rep. Conf. Electr. Insul. Diel. Phen. October 17-20, 1999, Austin, Texas, USA, 707-710.

[9] SOERQVIST, T.—VLASTOS, A.: Hydrophobicity Loss and Leakage Currents of Long-term AC and DC Energized Polymeric Insulators, Proc. Nordic Insul. Symp. (NORD-IS), June 10-12, 1996, Bergen, Norway, 249-256.

[10] WINDMAR, D.: Water Droplet Initiated Discharges in Air, PhD Thesis, Uppsala University, Uppsala, Sweden, 1994.

[11] SCHUTTE, T.: Water Drop Dynamics and Flashover Mechanisms on Hydrophobic Surfaces, Proc. Nord. Insul. Symp. (NODR-IS), June 15-17, 1992,Vasteras, Sweden, paper 8.1, 1-14.

[12] MACKY, W. A.: Some Investigation on the Deformation and Breaking of Water Drops in Strong Electric Fields, Proc. Roy. Soc. **133** (1931), 565-587.

[13] TAYLOR, G. I.: Disintegration of Water Drops in an Electric Field, Proc. Roy. Soc. **A280** (1964), 383-397.

[14] KAMRA, A. K.—AHIRE, D. V.: Wind-Tunnel Studies of the Shape of Charged and Uncharged Water Drops in the Absence or Presence of an Electric Field, Atmos. Res. **23** (1989), 117-134.

[15] WEIHE, H.—MACEY, R. E.—REYNDERS, J. P.: Field Experience and Testing of New Insulators in South Africa, CIGRE, 1980, Paper 22–03.

[16] DE TOURREIL, C.—BOURDON, P.—LANTEIGNE, J.: Aging of Composite Insulators Caused by Service and Simulated Service Conditions, CIGRE, 1986, Paper 15–01.

[17] KEIM, S.—KOENIG, D.: Vortraege der ETG-Fachtagung ,,Einfluss von Grenzflaechen auf die Lebensdauer elektrischer Isolierungen", September 21–22, 1999, Bad Nauheim, Deutschland, 123-128.

[18] DANIKAS, M. G.: Factors Affecting the Breakdown Strength of Transformer Oil, MSc Thesis, University of Newcastle-Upon — Tyne, Newcastle-upon-Tyne, England, 1982.

[19] ZHU, Y.—YAMASHITA, S.—ANAMI, N.—OTSUBO, M.—HONDA, C.—HASHIMOTO, S.—HASHIMOTO, Y.: Leakage Current Analysis and Electric Field Calculation in Salt Fog Ageing Test on Polymer Insulation Material, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 19-22, 2003, Albuquerque, New Mexico, USA, 92-95.

[20] KEIM, S.—KOENIG, D.—HINRICHSEN, V.: Experimental Investigation on Electrohydrodynamic Phenomena at Single Droplets on Insulating Surfaces, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 19–22, 2003, Albuquerque, New Mexico, USA, 133-136.

[21] GORUR, R. S.: High Voltage Outdoor Insulation Technology, Control and Dyn. Syst. **44** (1991), 131-191.

[22] KAMRA, A. K.—BHALWANKAR, R. V.—SATHE, A. B.: The Onset of Disintegration and Corona in Water Drops Falling at Terminal Velocity in Horizontal Electric Fields, J. Geophys. Res. **98** **(D7)** (1993), 12901-12912.

[23] GERODIMITROU, K.: Study of Water Droplet Behaviour on a Polymeric Insulating Surface, Diploma Thesis, Democritus University of Thrace, Department of Electrical and Computer Engineering, Xanthi, 2004 (in Greek).

[24] McGRATH, P. B.—KLAPP, D. A.—BURNS, C. W.: Laboratory Aging of Polymer Insulators, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 19–22, 2003, Albuquerque, New Mexico, USA, 402-405.

[25] PHILIPS, A. J.—CHILDS, D. J.—SCHNEIDER, H. M.: Aging of Non-ceramic Insulators due to Corona from Water Drops, IEEE Trans. Power Deliv. **4** **(3)** (1999), 1081-1089.

[26] WANG, S.—LIANG, X.—CHENG, Z.—WANG, X.—LI, Z.—ZHOU, Y.—YIN, Y.—WANG, L.—GUAN, Z.: Hydrophobicity Changing of Silicone Rubber Insulators in Service, CIGRE Paper 15–305, Session 2002.

Received 25 October 2005

Michael G. Danikas, born in 1957, Kavala, Greece, received his BSc and MSc degrees from the University of Newcastle-upon-Tyne, Dept. of Electrical and Electronic Engineering, England, and his PhD Degree from Queen Mary College, University of London, Dept. of Electrical and Electronic Engineering, England, in 1980, 1982 and 1985 respectively. From 1987 to 1989 he was a lecturer at Eindhoven University of Technology, The Netherlands, and from 1989 to 1993 he was employed at Asea Brown Boveri, Baden, Switzerland. He did work in the fields of partial discharges, vacuum insulation, polymeric outdoor insulation, rotating machine insulation and insulating systems at cryogenic temperatures. From 1993 to 1998 he was Assistant Professor at Democritus University of Thrace, Dept. of Electrical and Computer Engineering becoming an Associate Professor in the same department in 1998. During the periods 1999-2001 and 2003-2004 he was director of the Division of Energy Systems. His current research interests are breakdown in transformer oil, simulation of electrical tree propagation in polymers, study of partial discharge mechanisms in enclosed cavities, study of circuit parameters on the measured partial discharge magnitude and surface phenomena in indoor and outdoor high voltage insulators. He continues his cooperation with Lectromechanical Design Co., Herndon, Virginia, USA, on the influence of very small partial discharges on polymeric materials.

Paschalis Rakitzis was graduated from Democritus university of Thrace, Department of Electrical and Computer Engineering, Xanthi, Greece, in 2000. He did his diploma thesis on electric energy systems. He was awarded an MSc from the same department in 2003. He did research on polymeric surface phenomena under high voltages. He is currently employed with the company "Xanthi Cables" where he is responsible for quality control.

Konstantinos Karakoulidis received his diploma in Electrical Engineering from Aristotle University of Thessaloniki, Department of Electrical Engineering, Thessaloniki, Greece in 1988. His diploma thesis at that time was on breakdown of long air gaps. He received his MSc from Democritus University of Thrace, Department of Electrical and Computer Engineering, Xanthi, Greece, in 2002. He currently teaches at the Technological and Educational Institute of Kavala, Department of Electrical Engineering, Kavala, Greece. Among his research interests are the breakdown of long air gaps and surface phenomena under high voltages.