

ROOM TEMPERATURE VULCANIZED (RTV) SILICONE RUBBER COATINGS ON GLASS AND PORCELAIN INSULATORS: AN EFFORT TO MODEL THEIR BEHAVIOUR UNDER CONTAMINATED CONDITIONS

Alexandros Theodoridis^{*} — Michael G. Danikas^{*}
— Johannes Soulis^{**}

In polluted environments, coatings of room temperature vulcanized (RTV) silicone rubber are increasingly used on glass and porcelain insulators. During the lifetime of insulators, chemical changes and chemical reactions occur on the surface and in the bulk of the coatings. These reactions can lead to the formation of low molecular weight (LMW) silicone fluid. Factors that influence the quantity of low molecular weight silicone fluid in the coatings are investigated here. It is of great importance to know the behaviour of LMW silicone fluid in the coatings since the hydrophobicity of the latter depends to a great extent on the diffusion of the LMW silicone fluid to the coating surface. A mathematical model to describe the phenomenon of the diffusion of the low molecular silicone fluid from the bulk to the surface of the coating is proposed. It is the first time that such a model — including many parameters — is proposed. The proposed model deviates from the well known Fick's equation of diffusion. A relevant discussion about the applicability of the model is given.

Key words: Silicone rubber coating, outdoor insulator, low molecular weight silicone fluid

1 INTRODUCTION

Polymeric insulators represent an alternative to the use of glass and porcelain insulators. The history of polymeric insulators began in the 1940s when organic insulating materials were used to manufacture high voltage indoor electrical insulators from epoxy resin. These materials were lightweight, impact resistant and could be used to form large complex parts. Polymeric insulators for outdoor application on transmission lines were not developed until the late 1960s and 1970s. Polymeric insulators finally came into general use on transmission lines in the 1980s. Polymers are in general preferable to porcelain and/or glass because of their lightweight, better resistance to vandalism and superior contamination performance [1–3].

Many materials have been tried for outdoor insulation applications. These materials include silicone rubber, ethylene propylene rubber (EPR), epoxy resin, teflon, polyethylene, ethyl vinyl acetate (EVA), modified polyolefins, *etc.* Among these, silicone rubber is used in two forms: either as a room temperature vulcanized (RTV) sprayable coating on porcelain or glass insulators and as an RTV elastomer for weathersheds, or as a high temperature vulcanized (HTV) elastomer for weathersheds on outdoor insulation. EPR is the generic name for two types of material, a copolymer of ethylene and propylene monomers known as EPM, and a terpolymer of ethylene,

propylene and diene monomers known as EPDM. Many of today's polymer insulators consist of either HTV silicone rubber or EPR regarding their weathershed material [4].

The general advantages of polymeric insulators over glass and porcelain insulators are the hydrophobic properties of their surface and — in some of them — the retention of these properties, their resistance to vandalism due to their non-brittle and flexible nature and the fact that — because of their lesser weight in comparison to porcelain and glass insulators — their supporting structures, such as poles and towers, can be of reduced dimensions and can be accommodated in a limited right of way passage [4].

While solving many of the problems commonly experienced with porcelain and glass, the use of polymers have created new problems which were not experienced before. A serious problem is material ageing, which results from a loss of useful insulating properties with time. The organic nature of the polymer makes it susceptible to many elements experienced in service, such as mechanical loading, electric stress, contamination, ultra-violet (UV) radiation, automobile emissions, moisture, *etc.* The problem is even more complicated as most of the above factors exist simultaneously and have a synergistic effect on ageing. The resultant effect of ageing can be a gradual loss of mechanical strength, material degradation in the form

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

^{**} Democritus University of Thrace, Department of Civil Engineering, Division of Hydraulics, 67100 Xanthi, Greece

of tracking and erosion of the weathershed and flashover leading to power outages [4].

Problems to polymeric insulators may also arise because of poor bonding between the rod and the housing material, poor bonding between the weathershed and the insulation of the rod, inadequate attachment of the rod to the metallic fittings and improper selection of insulating material itself, which may be prone to electrical deterioration [5, 6].

Besides the insulators that are wholly made of polymeric materials, there is another category of insulators in use over the last three decades. These insulators are porcelain / glass insulators coated with polymeric materials. A widely used material for making such coatings is the room temperature vulcanized (RTV) silicone rubber. Silicone rubber imparts its hydrophobic property to the surface of porcelain / glass insulators. Thus, the formation of continuous water layers and the occurrence of leakage currents on the surface of insulators is prohibited resulting in an increase to their flashover voltage. Furthermore, this polymer is able to encapsulate contaminants which exist on its surface and therefore the probability of formation of a contamination layer on the insulator surface is reduced. It should be mentioned that this kind of insulators has improved resistance to tracking and erosion since coatings contain materials with high thermal conductivity coefficients. It is true that, under severe weather conditions, hydrophobicity is temporarily lost and as a result dry band arcing and leakage currents appear on the surface of insulators. However, this important property is recovered after some time due to the diffusion of low molecular weight (LMW) silicone fluid from the bulk to the surface of the coating.

The question, however, remains as to whether such a thin RTV coating (the thickness of which generally is of the order of ~ 1 mm) can preserve hydrophobicity even under heavily polluted conditions. In other words, if one considers the silicone rubber coating as a 'reservoir' of LMW parts, are there any conditions under which it comes to an exhaustion of this 'reservoir'? [7] There are already suggestions that a 'fatigue' process may exist in silicone rubber coatings [8, 9]. In this paper, we tackle this question and we try to mathematically express the diffusion of LMW silicone fluid from the bulk to the surface of the coating. Firstly, phenomena that take place both on the surface and in the bulk of coatings as well as the numerous factors influencing them are being considered.

2 CHEMICAL CHANGES ON THE SURFACE AND IN THE BULK OF THE SILICONE RUBBER COATING. FORMATION OF LMW SILICONE FLUID

The tendency of RTV coatings to form lower molecular weight polydimethylsiloxane (PDMS) oligomers (silicone fluid) as a result of heat generated by dry band arcing in wet conditions is probably due to bond scission. This results in the formation of smaller molecules concomitant

with crosslinking of the remaining body of the polymer at the surface (or just below). Also, under a given set of conditions, oligomers that exist in the main body of the polymer can diffuse to the surface when erosion occurs [10]. Possible chemical changes due to heat from dry band arcing are, a) instantaneous dissociating on the surface at very high temperature and b) slow dissociation or chemical reactions due to conduction of heat into the coating.

Chemical reactions that occur are associated with:

a) *Scission and interchange of bonding or of chains.* The heat from dry band arcing is probably sufficient to cause chemical reactions at the surface. The scission can result from the heat of dry band arcing. The heat probably causes scission of $-CH_3$ groups from Si in PDMS chain and of polymer backbone, and at the same time creates free radicals. The chain with scission is followed by interchange of chain backbone. However, not all scissions result in free radicals. In some cases a break results in effective hydrolysis and crosslinking due to a hydrogen transfer. It is also possible to form short chain PDMS molecules.

b) *Hydrolysis of siloxane bonds and hydrocarbon groups.* In the presence of moisture, a reaction of hydrolysis will occur, *ie* with water acting as co-catalyst. Under electrical stress, moisture could be dissociated due to heat from dry band arcing and electrolysis to $-OH$ and $-H$ from H_2O . The free radicals from hydrocarbon groups probably react with $-OH$ from H_2O . The free radicals in the backbone of PDMS also react with $-OH$ from H_2O . The rate of scission will be proportional to the water concentration and the position of equilibrium will be determined by the water content of the system. The rate of scission due to this reaction should be at maximum when the environment is saturated with water vapour.

c) *Oxidation of hydrocarbon groups and crosslinking of siloxane bond.* The hydrolysis is followed by oxidation of hydrocarbon groups and crosslinking of siloxane bonded polymer. It is also possible to form short chain of PDMS. The possibility that the hydrolysis and crosslinking or oxidation occur simultaneously at high temperature has been noticed. The LMW PDMS (silicone fluid) could be formed under dry band arcing and it is possible to explain that the scission of backbone and interchange of bonding is responsible to form the silicone fluid.

It is suggested that siloxane is converted initially to silanols and cross-linked siloxane is formed from the organosilanols during the dry band arcing. Silicone fluid is present originally as a plasticizer in the rubber and is also formed in the bulk due to the heat from dry band arcing. Thereafter it diffuses to the surface of RTV coating and through the contaminant layer [4], [10], [11], [12]. Pyrolysis at the surface of RTV coatings may also result from the high temperatures of the dry band arcing [12].

3 FACTORS AFFECTING THE QUANTITY OF LMW SILICONE FLUID AND ITS DIFFUSION TO THE SURFACE OF THE COATING

The content of the LMW fluid increases with increasing size of the particles of the alumina trihydrate filler (1–75 μm) assuming that the samples are not stressed in a salt-fog chamber [13, 14]. That may be due to the effect of the fluid adhering to the surface of the filler particles within the formulated compound and thus not being able to diffuse out. Regarding the diffusion of the fluid, the weight loss of LMW fluid from the surface of the coating is independent of the size of alumina trihydrate in the above mentioned particle range [13].

There is an optimum filler level for a particular size of filler particles giving the best performance in contaminated conditions since a very high concentration of filler leads to a higher thermal conductivity and to a more effective transfer of heat to the substrate but, on the other hand, with increasing filler concentration, the surface roughness increases and the amount of the LMW fluid decreases [13, 15].

No particular dependence of the diffusion of LMW fluid on the solvent type or on the speed of the wind was observed [13]. On the contrary, a slight reduction of the concentration of the silicone fluid in coatings immersed in water for 14 months was observed. This was attributed to the dissolution of LMW silicone fluid in the water [13].

The amount of silicone fluid on the surface of the coatings increased with increasing the amount of added of silicone fluid by weight to the RTV formulation [16]. Furthermore, the formation of silicone fluid on the surface of the coatings increased with increasing heat produced. However, the heat of a persistent dry band arcing causes more damage to the surface than benefit because of its intensity, which leads to very high temperatures resulting in a net decrease in the content of the LMW silicone fluid [17].

Regarding the coating thickness, the quantity of the silicone fluid is greater in thicker coatings since the latter contain bigger masses of silicone rubber. The diffusion of LMW silicone fluid, on the other hand, increases with increasing coating thickness. The thicker coating is likely to maintain a hydrophobic surface for a longer time than a thinner coating. The thicker coating, however, develops more intense discharges for the same applied electric stress than the thinner coating. It is anticipated that an optimum thickness of RTV coating exists which may be of benefit in the case of porcelain insulators [18].

The content of the LMW silicone fluid decreased with increasing duration of the test in an energized salt-fog chamber, a fact which may be attributed to dry band arcing activity being more intense for longer test times [14, 15]. The content of the LMW silicone fluid increased with increasing recovery time in air after the test in the energized salt-fog chamber, probably because of the diffusion of silicone fluid from the bulk of the coating to its surface during recovery time [11, 13, 14, 17]. Moreover, it was reported that the initial leakage current increased

with increasing time during which the specimen remains in the salt-fog chamber without being subjected to an electrical stress, a phenomenon which is consistent with the observed gradual decrease of the contact angle with increasing residence time in the salt-fog chamber [19].

4 MATHEMATICAL MODELLING OF THE DIFFUSION OF THE LMW SILICONE FLUID FROM THE BULK TO THE SURFACE OF THE COATING

The existence of a mathematical model that will describe the diffusion of the LMW silicone fluid from the bulk of the coating to its surface is of great significance. With the help of such a model, the quantity of the fluid at every point of the coating at every instant may be known. Such knowledge is important because it can to a certain extent answer the questions put forward in [7].

Not much work has been reported regarding the modelling of the diffusion of the LMW silicone fluid. In [4], for example, it was proposed that the diffusion of the LMW silicone fluid can be expressed as

$$M_t/M_0 = 4(Dt/\pi l^2)^{1/2} \quad (1)$$

where, M_t is the change in mass after time t , M_0 is the initial mass, t is the time, D is the diffusion coefficient in and l the sample thickness. The above equation assumes that the diffusion coefficient D is constant and it suggests that if the weight loss is plotted as a function of $t^{1/2}$ the graph should be a straight line, as all other parameters in Eq. (1) are constant. The latter assumption, however, is not always correct since many parameters come into play. The above equation as well as the ones included in standard textbooks [20] are based on Fick's law and they do not apply since LMW silicone fluid diffusion is a complicated phenomenon and many parameters are involved [21]. To the best of our knowledge, there is no other technical literature tackling the problem of the diffusion of LMW silicone fluid from the bulk to the surface of the coating.

The phenomenon of the diffusion of a fluid in a solid material occurs not only in electrical engineering but also in civil engineering. Thus, civil engineers study, among others, the diffusion of water in a dam. With the help of computational fluid mechanics, engineers have managed to describe this phenomenon and they have given numerical solutions to such problems. Numerical models use the Finite Element Method, the Finite Difference Method and the Finite Volume Method. The last method is the best one since it comprises the advantages of the first two methods without having their disadvantages [22]. In [23], the following equation, dealing with the diffusion of water in a dam was reported

$$\frac{\partial \Theta_w}{\partial t} = \frac{\partial}{\partial x} \left[D(\Theta_w) \frac{\partial \Theta_w}{\partial x} \right] + \frac{\partial}{\partial z} \left[D(\Theta_w) \frac{\partial \Theta_w}{\partial z} \right] + \frac{\partial K(\Theta_w)}{\partial z} \quad (2)$$

where, x and z are spatial coordinates, t the time, Θ_w is the per volume moisture of ground, $K(\Theta_w)$ the permeability coefficient as a function of the per volume moisture of ground, $D(\Theta_w)$ the diffusion coefficient as a function of the per volume moisture of ground. The above equation has been solved using the Finite Volume Method and with the help of a computer.

The above equation can be adapted to the case of glass and/or porcelain insulators coated with silicone rubber. In silicone rubber coatings, not only is the low molecular weight silicone fluid inherently present but also it is formed under certain conditions. According to thermodynamic laws, and as mentioned in [14] and [19], the silicone fluid diffuses to the surface from the bulk until equilibrium is reached. After making the necessary changes to the above equation, the equation that describes the motion of the silicone fluid in the coating can be formulated as

$$\frac{\partial C_{lmw}}{\partial t} = \frac{\partial}{\partial x} \left[D(C_{lmw}) \frac{\partial C_{lmw}}{\partial x} \right] + \frac{\partial}{\partial z} \left[D(C_{lmw}) \frac{\partial C_{lmw}}{\partial z} \right] + \frac{\partial K(C_{lmw})}{\partial z} \quad (3)$$

where, x and z spatial coordinates, t the time, C_{lmw} the concentration of the low molecular weight silicone fluid in the coating, $K(C_{lmw})$ the permeability coefficient as a function of the concentration of the low molecular weight silicone fluid in the coating, $D(C_{lmw})$ the diffusion coefficient as a function of the concentration of the low molecular weight silicone fluid in the coating. This equation is valid for two-dimensional problems.

The above equation can take a three-dimensional form:

$$\frac{\partial C_{lmw}}{\partial t} = \frac{\partial}{\partial x} \left[D(C_{lmw}) \frac{\partial C_{lmw}}{\partial x} \right] + \frac{\partial}{\partial y} \left[D(C_{lmw}) \frac{\partial C_{lmw}}{\partial y} \right] + \frac{\partial}{\partial z} \left[D(C_{lmw}) \frac{\partial C_{lmw}}{\partial z} \right] + \frac{\partial K(C_{lmw})}{\partial z} \quad (4)$$

In the case, where it is considered that the influence of gravity is negligible for the development of diffusion, the partial derivative $\frac{\partial K(C_{lmw})}{\partial z}$, present in the second part of the equation, can be omitted.

It should be noted that the diffusion and permeability coefficients are functions of many variables, which are the size of filler particles, the filler concentration, the coating thickness, the coating temperature and the humidity. The above equations can be solved with the help of a computer and appropriate software. However, there are some requirements that have to be fulfilled for the solution to be possible. These requirements include the determination of initial and boundary values as well as the determination of the function $D(C_{lmw})$. In the case in which gravity has to be taken in mind, the function $K(C_{lmw})$ has also to be determined. Determining the initial values means the determination of the value of the concentration of the low molecular weight silicone fluid at time $t = 0$, which can be considered as the time when the insulator starts functioning. Determining the boundary values means the

determination of the value of the concentration of the low molecular weight silicone fluid at the interface of coating and insulator material (porcelain or glass) and at the interface of coating and atmosphere for all times. For the determination of the $D(C_{lmw})$ and $K(C_{lmw})$ functions, experiments should take place. These experiments will give the values of the diffusion and permeability coefficients for different values of the concentration of the LMW silicone fluid. It should be noted that the experiments have to be carried out with great care. The phenomena are non-linear and a false measurement can lead to wrong results. Finally, experiments have to be carried out in order to determine the diffusion and permeability coefficients as a function of the size of filler particles, the filler concentration, the coating thickness, the coating temperature and the humidity.

The above mathematical model can also be applied to the case in which the insulator is wholly made of polymeric materials. However, in this case some changes have to be made concerning the determination of the boundary values since the interface of coating and insulator material (porcelain or glass) does not exist.

Comparing the above model with that reported in [4], one can see that there are several differences. In [4], a constant diffusion coefficient is used while in the above model, D is a function of many variables. Gravity is neglected in [4], something which is not valid for the above model, since the permeability coefficient appears. Finally, the above mathematical model gives the concentration of the LMW silicone fluid both in time and in space (in the coating), while in [4], only the variation in time is provided. Therefore, we believe that the description of the silicone fluid diffusion with the above model is much more complete.

5 CONCLUSIONS

With the use of the proposed model, the determination of the concentration of the low molecular weight silicone fluid in time and at every point of the coating may be possible. To the best of our knowledge, this is the first time that an equation (regarding the diffusion of LMW silicone fluid from the bulk to the surface) including so many parameters is proposed. The knowledge of the silicone fluid quantity in the coating is very important since it will help engineers to assess the state of the coating and - to a certain extent - that of the insulator

REFERENCES

- [1] SCHNEIDER, H. M.—HALL, J. F.—KARADY, A. A.—RENOWDEN, J.: Nonceramic Insulators for Transmission Lines, IEEE Trans. Power Deliv. **4** No. 4 (1989), 2214–2221.
- [2] HALL, J. F.: History and Bibliography of Polymer Insulators for Outdoor Applications, IEEE Trans. Power Deliv. **8** No. 1 (1993), 376–378.
- [3] DANIKAS, M. G.: Polymer Outdoor Insulators, Acta Electrotechnica Napocensis **40** No. 1 (1999), 3–10.

- [4] GORUR, R. S.: High Voltage Outdoor Insulation Technology **44** (1991), 131–191.
- [5] STARR, W. T.: Polymeric Outdoor Insulation, IEEE Trans. Electr. Insul. **25** No. 1 (1990), 125–136.
- [6] LOOMS, J. S. T.: Insulators for High Voltages, Peter Peregrinus, London, 1988.
- [7] DANIKAS, M. G.—GUBANSKI, S. M.: Experience with the Merry-go-round Test, IEEE Trans. Electr. Insul. **27** No. 5 (1992), 1058–1060.
- [8] VLASTOS, A. E.—GUBANSKI, S. M.: Surface Structural Changes of Naturally Aged Silicone and EPDM Composite Insulators, IEEE Trans. Power Deliv. **6** No. 2 (1991), 888–900.
- [9] GUBANSKI, S. M.—VLASTOS, A. E.: Wettability of Naturally Aged Silicone and EPDM Composite Insulators, IEEE Trans. Power Deliv. **5** No. 4 (1990), 2030–2038.
- [10] KIM, S. H.—CHERNEY, E. A.—HACKAM, R.—RUTHERFORD, K. G.: Chemical Changes at the Surface of RTV Silicone Rubber Coatings on Insulators during Dry-Band Arcing, IEEE Trans. Diel. Electr. Insul. **1** No. 1 (1994), 106–123.
- [11] KIM, S.-H.—CHERNEY, E. A.—HACKAM, R.: Suppression Mechanism of Leakage Current on the RTV Coated Porcelain and Silicone Rubber Insulators, IEEE Trans. Power Deliv. **6** No. 4 (1991), 1549–1556.
- [12] KIM, S.-H.—CHERNEY, E. A.—HACKAM, R.: Effect of Dry Band Arcing on the Surface of RTV Silicone Rubber Coatings, Conf. Rec. IEEE Int. Symp. Electr. Insul., June 7–10, 1992, Baltimore, USA, 237–240.
- [13] DENG, H.—HACKAM, R.: Low-molecular Weight Silicone Fluid in RTV Silicone Rubber Coatings, IEEE Trans. Diel. Electr. Insul. **6** No. 1 (1999), 84–94.
- [14] DENG, H.—HACKAM, R.—CHERNEY, E. A.: Role of the Size of Particles of Alumina Trihydrate Filler on the Life of RTV Silicone Rubber Coating, IEEE Trans. Power Deliv. **10** No. 2 (1995), 1012–1024.
- [15] KIM, S.-H.—CHERNEY, E. A.—HACKAM, R.: Effects of Filler Level in RTV Silicone Rubber Coatings Used in HV Insulators, IEEE Trans. Electr. Insul. **27** No. 6 (1992), 1065–1072.
- [16] DENG, H.—HACKAM, R.—CHERNEY, E. A.: Influence of Thickness, Substrate Type, Amount of Silicone Fluid and Solvent Type on the Electrical Performance of RTV Silicone Rubber Coatings, IEEE Trans. Power Deliv. **11** No. 1 (1996), 431–443.
- [17] KIM, S.-H.—HACKAM, R.: Formation of Silicone Fluid at the Surface of RTV Silicone Rubber Coating due to Heat, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 17–20, 1993, Pocono Manor, PA, USA, 605–611.
- [18] DENG, H.—HACKAM, R.: Electrical Performance of RTV Silicone Rubber Coating of Different Thicknesses on Porcelain, IEEE Trans. Power Deliv. **12** No. 2 (1997), 857–866.
- [19] KIM, S.-H.—CHERNEY, E. A.—HACKAM, R.: Hydrophobic Behavior of Insulators Coated with RTV Silicone Rubber, IEEE Trans. Electr. Insul. **27** No. 3 (1992), 610–622.
- [20] BRODLEY, R. S.—HERSHEY, H. C.: Transport Phenomena., McGraw-Hill, New York, 1988.
- [21] DANIKAS, M. G.—HACKAM, R.: Low-Molecular Weight Silicone Fluid in RTV Silicone Rubber Coatings, IEEE Trans. Diel. Electr. Insul. **7** No. 3 (2000), 461–462.
- [22] SOULIS, J.: Computational Fluid Mechanics, Democritus University of Thrace, Xanthi, 1986. (in Greek)
- [23] KOUDOUMAKIS, P.: Unsaturated Flow through a Dam During the Filling of a Reservoir, MSc Thesis, Democritus University of Thrace Xanthi, Greece, 2000. (in Greek)

Received 9 October 2000

Alexandros Theodoridis graduated in 2000 from the Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece. He is currently pursuing a Master's degree at the same university. His research interests lie for the time being in Power Electronics and related applications.

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 the Eindhoven University of Technology, The Netherlands, and from 1989 to 1993 he was employed at Asea Brown Boveri, Baden, Switzerland. He researched 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, Department of Electrical and Computer Engineering. In 1998 he became Associate Professor in the same department. During the academic years 1999-2000 was elected director of the Division of Energy Systems. He was reelected director for the academic year 2000-2001. His current research interests are breakdown in transformer oil, simulation of electrical treeing 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 hv insulators.

Johannes Soulis was born in 1950. He is Associate Professor in the Department of Civil Engineering, Democritus University of Thrace, Xanthi, Greece. He carried out his PhD studies at Oxford University, England, and is currently involved in research regarding diffusion phenomena and flow dynamics. He is the author of numerous journal and conference papers as well as of several books on hydraulics. He is strongly interested in the interdisciplinary applications of his research.