Modelling Partial Discharge Phenomena

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Summary

The aim of this paper is to highlight the origins and limitations of physical concepts used in PD models, most of which can be traced back to original work reported over 60 years ago, with a view to helping inform researchers developing the next generation of PD models and practitioners who may be using simulation results to inform decisions.

Introduction

Measurements of partial discharge (PD) activity are a commonly used technique to diagnose the health of insulation material within high voltage plant. The definition of PD is relatively broad, it is generally defined as a localised or confined discharge within an insulating medium [1]. Due to the high electric breakdown strength of insulation materials PDs typically occur within low density defects in the system. One family of defects which have received significant research attention are air-filled voids, typically spherical or cylindrical, surrounded by solid dielectric material. Experiments have typically used a `sandwich' technique to fabricate cylindrical voids, using three slabs of material with a circular hole drilled into the central slab. The slabs are then pressed together and placed between parallel plate electrodes. A common dielectric material used to fabricate cylindrical voids is LDPE [2]. By injecting air through a syringe before the curing process spherical voids have been fabricated in epoxy resins [3,4] and silicone rubber [5].

PD activity models have been developed by the research community in the literature and have been shown to reproduce data from these simple experiments. However, there is still significant progress to be made both in the physical understanding of PD and the experimental techniques available before field data can be fully interpreted using simulation models. The current generation of PD activity models typically use the same approach, and make the same assumptions, as those introduced by Niemeyer and others in the early 1990's. The origin of many of these assumptions can be traced to experimental investigations conducted in the 1960's and 1970's.

The discussion in this article will be restricted to PD in AC systems with discharges occurring inside air-filled voids. This is still a fairly broad scope and covers the majority of the PD simulation work in the literature. The motivation for this is that there are many works which have simply taken the equations used in early work without knowledge of their origins and as a result they do not fully consider their limitations. This article is intended to inform future research developing new and improved models of PD.

Simulating Partial Discharge Activity

In order for a discharge to initiate it is generally accepted that two conditions are necessary. Firstly, that there is a sufficiently high electric field over a sufficiently large region. Secondly, an initial seed electron is available.

The electric field accelerates the seed electron to an extent that collisional ionisation can take place. Collisional ionisation is a process by which a high energy electron strikes and ionizes a neutral molecule to produce another electron and a positive ion. If the electric field is sufficiently high this process continues as a chain reaction increasing the number of charged species, this is known as an electron avalanche. A Townsend discharge consists of a series of electron avalanches, for this to be self-sustaining then secondary processes, such as charge emission from irradiated metallic surfaces, is required. If the number density of the charged species is sufficiently high that the local field produced by the charged species begins to shield the avalanche interior a new discharge mechanism can take place. This is because as the avalanche shields its interior it causes an enhancement in the region outside of it. If this field is sufficiently high it can generate an ionising wave, typically referred to as a streamer [6]. The speed of the streamer front far exceeds the electron drift velocity, resulting in discharges which take place in the timescale of nanoseconds. When a PD reaches a dielectric barrier it will deploy surface charge which opposes the discharge field, reducing the ionisation rate and thus extinguishing the discharge [6].

In order to simulate PD activity it is therefore necessary to have knowledge of the availability of seed charges and the electric field within a defect. It is then necessary to develop a simple model of how a discharge will influence these processes. PD activity models typically make the following simplifying assumptions:

1. Although discharge initiation and propagation will depend on the electric field strength over a given region it is typically assumed that the electric field within voids in PD systems is close to uniform, or that PD inception is controlled by the electric field magnitude at a single point in the void, typically the centre of the void. If this value is greater than some inception field it is then supposed that the electric field is sufficient for a discharge to take place.
2. A PD is effectively modelled as a step change in the surface charge density at the void boundary [4], or in the conductivity of the void [7], and acts to reduce the electric field within the void to some residual field.
3. The same presumption is made regarding electron generation processes, they are all controlled by a single value of the electric field.

The equations governing the inception field, residual field and electron generation are provided in the work of Niemeyer. They have been largely unchanged when used by other authors and are effectively regarded as fundamental when simulating PD activity. In the next sections an overview of the origins of these equations is undertaken, and using this information a critique of their applicability to PD modelling is provided.

Inception Electric Field

PD activity models use an inception field, typically denoted as E_{inc}, to determine whether the electric field is sufficient for a discharge to take place. The inception field for an air gap that is typically used in the PD activity literature is introduced in [8]

$$E_{\mathrm{inc}} = Ap\left(1 + \frac{B}{(pL)^{1/2}}\right) \tag{1}$$

where A and B are constants, L is the gap length and p is the air pressure. Despite the widespread usage of (1) it does not always appear that its origins, including the theoretical and experimental evidence behind it, is widely known. In this section a derivation of (1) is presented, including a summary of the original experimental investigations used to determine it and a discussion of its applicability to PD systems.

The empirical evidence behind (1) is a series of experiments undertaken in the 1960's by researchers at the University of Strathclyde [9]. These experiments consisted of measuring the 'sparkover' (a term synonymous with breakdown) voltage of parallel plate electrodes in air at atmospheric pressure and humidity. The experimental data could be fitted by the curve

$$V_{\mathrm{spark}} = CL + D\sqrt{L} \tag{2}$$

where $C = 2.449$ kV/mm and $D = 2.09$ kV/mm. As the breakdown voltage is a function of pL from Paschen's law, and using the fact that the experiment was performed at atmospheric pressure $p = p_0 = 101325$ Pa, it follows that

$$V_{\mathrm{spark}} = (C/p_0)pL + D/p_0^{1/2}\sqrt{pL}. \tag{3}$$

Setting the inception field equal to the 'sparkover' field

$$E_{\mathrm{inc}} = \frac{V_{\mathrm{spark}}}{L} \tag{4}$$

it follows that the constants A and B in (1) can be written as

$$A = \frac{C}{p_0} = 24.2 \text{ V Pa}^{-1}\text{ m}^{-1} \tag{5}$$

$$B = \frac{D}{p_0^{1/2}A} = 8.6 \text{ Pa}^{1/2}\text{ m}^{1/2} \tag{6}$$

these values for A and B are provided in [10]. It is of interest to note that the values of A used in [3], used subsequently by a number of authors, is 25.2 V Pa^{-1} m^{-1}. This appears to be a typographical error, however, this is not of particular significance as the error it introduces is approximately 5%.

From (1) it is clear that regardless of gap length L the electric field must still exceed Ap in order for discharges to take place. In [11] Ap is referred to as a limiting field, more commonly it is defined as the critical field E_{cr}. Below the critical field attachment processes dominate ionisation processes and charge multiplication cannot take place. In [8] A is rewritten as $(E/p)_{\mathrm{cr}}$ to demonstrate that it is a constant of proportionality between the critical field and the air pressure. As an aside at atmospheric pressure $E_{\mathrm{cr}} = (E/p)_{\mathrm{cr}}\, p = 2.45$ kV/mm which is a typical value for the breakdown strength of long air gaps.

It must be noted that the experiments performed by Strathclyde, [9], were conducted under a uniform field between metallic electrodes for air gaps between 3.5 cm to 17 cm. Furthermore, the authors took great care to clean the electrodes to keep them free from dust, and indeed observed an unacceptable scatter when the electrodes were placed in open atmosphere, resulting in the measurements being performed in an enclosure [9]. The 'sparkover' voltage obtained in these conditions is not necessarily going to be applicable to PD experiments. One simple reason is that the air gaps used in the experiment are simply too large. In many PD experiments voids are fabricated with air gaps less than 5 mm, therefore when using (1) a researcher is performing a significant extrapolation out of the range of the data that it is derived from. Another issue is that the sparkover experiment was performed between metallic electrodes. In PD experiments voids are typically bounded by insulation material. This material may well have very different secondary emission characteristics to metals, which could influence the inception field. Furthermore, the complexity of fabricating voids in dielectric material may lead to changes in humidity and contaminate the void surface, and as previously discussed (1) was determined from carefully controlled experiments. Another key point is that in [8], (1) is assumed to hold over many stages of PD activity, with the pressure altered as a free parameter such that the model fits measured data. This is not especially accurate, firstly because (1) is derived for gaps containing air. It is likely that discharge activity will rapidly remove the oxygen and form by-products at the void surface resulting in a void containing mostly nitrogen. It is argued in [8] that the gaseous products formed due to discharge activity will have fairly similar ionisation characteristics, although this is not completely convincing. Furthermore, (1) assumes that the electric field within a void is uniform. By-products on the void surface, such as oxalic acid crystals in LDPE [2], could produce high field points leading to divergent fields.

As was noted previously, PD activity models interpret E_{inc} as the minimum electric field required for a discharge to take place within a defect. This may seem to correspond with the PD inception voltage (PDIV), which is determined as the voltage at which PD activity begins [12]. However, E_{inc} is used within models to simulate PD activity, in other words it is the electric field required for discharges to take place during a period after the first discharge. The interpretation within a PD activity model is therefore that E_{inc} is electric field that corresponds to the PD extinction voltage (PDEV), the minimum voltage required to sustain PD activity. Considering E_{inc} as the electric field corresponding to PDEV has been shown to be quite reasonable for some experimental data [13]. A possible reason for why the PDIV exceeds PDEV is that in voids surrounded by dielectric material the mechanism by which seed charge is available for the first PD may require a higher electric field. This may not be the case for voids bounded by metallic electrodes, which were used to determine (1), due to their differing secondary emission characteristics.

Discharges in PD experiments may frequently take place in environments which differ from the carefully controlled conditions used to determine (1). These reasons are not sufficient to say that (1) cannot be used when analysing PD systems. However, it should be realised that deviations from it are not unexpected, and it should be interpreted as an approximation applicable to the initial stages of PD activity rather than a physical law.

Residual Electric Field

After a PD has taken place it is typically assumed that the electric field within the void falls to some residual value E_{res}. In [8] it is stated that for streamer discharges this is assumed to be the field in the channel of the streamer, E_{ch}, which is proportional to the critical field required to sustain the streamer

$$E_{\mathrm{res}} = E_{\mathrm{ch}} = \gamma E_{\mathrm{cr}} = \gamma (E/p)_{\mathrm{cr}}\, p \tag{7}$$

the constant of proportionality γ is set to 0.35 which is the average of two values, 0.2 and 0.5, obtained for positive and negative streamers respectively [8].

An equation providing the constant of proportionality γ between the channel field E_{ch} and the critical field E_{cr} is not explicitly present in the references provided for it, which is a topical review by Gallimberti [14]. In an earlier paper, [15], a channel field is not mentioned, E_{res} is instead set equal to the stability field, E_{g}, which would appear to refer to the experimental investigations conducted by Phelps, [16], which are mentioned in Gallimberti's review [14]. This work investigated the uniform background electric fields required for discharges to propagate in air after inception. The experimental arrangement consisted of two parallel plates with a hole drilled into the bottom plate. Into this hole a needle electrode was placed, the hole was then filled with insulation material to prevent breakdown between the bottom electrode and the needle electrode. A constant DC voltage was applied between the plate electrodes to create a uniform background field and an impulse voltage was applied to the needle electrode. The impulse voltage was sufficient to initiate a discharge from the tip of the needle while also occurring over a timescale short enough that breakdown did not occur across the gap. Phelps then analysed the impact of different uniform background fields of discharge propagation between the plate electrodes.

The minimum uniform background field, referred to as the stability field, required for a positive streamer at atmospheric pressure and humidity was determined to be approximately 0.5 kV/mm with a plate separation of 9 cm [16]. $E_{\mathrm{cr}} = (E/p)_{\mathrm{cr}}\, p = 2.45$ kV/mm at atmospheric pressure and humidity, which would correspond with the value of $\gamma = 0.2$ for positive streamers. For negative streamers Phelps does not appear to have determined a stability field, it is stated in [16], that “Negative streamers show only a small length enhancement with ambient fields as high as 0.8 kV/mm.” It is therefore unclear where the value of $\gamma = 0.5$ for negative streamers, stated in [8], originates from. It is worth noting that in earlier work, [15], γ is set to 0.2, the value for positive streamers.

It is possible that the review performed for this article missed relevant information; on the basis of the investigation performed so far there is some cause for concern on the robustness of (7). Firstly, it is not clear how the field required for a discharge to propagate across a gap, i.e. the stability field, relates the electric field after the discharge has ceased, i.e. the residual field. For PD experiments in particular, the void sizes are typically much smaller than those considered in Phelp's experiments which could influence the plasma dynamics. Furthermore the residual field will be significantly influenced by the surface charge deployed at dielectric boundaries, which are not present in the stability field experiments. It should be stated clearly that PD activity models consider surface charge to be deployed by the discharge to reduce the electric field to its residual value E_{res}. The point made here is that the equation used to determine the residual field value, (7), is based on stability field measurements which as an approach is questionable. It is also unclear how this relates to the channel field, E_{ch}, of the discharge.

Plasma dynamic simulations performed in a 1 mm diameter air filled void suggested that a discharge would completely `short' the electric field, meaning $E_{\mathrm{res}} \approx 0$ [17]. For a thin 100 µm high cylindrical void a similar investigation demonstrated that the residual field was dependent on the magnitude of the discharge [13]. The results of simulation investigations combined with the uncertainty in the origins of (7) merit further investigation. On the information available thus far it seems questionable to assume that the electric field in a defect after a discharge will always fall to a fixed residual value.

Electron Generation Rate

The availability of a seed electron is typically treated as a stochastic process, where at each model time step the following condition is checked

$$1 - \exp\left(\dot{N}_{\mathrm{e}} \Delta t\right) > R \tag{8}$$

where $\dot{N}_{\mathrm{e}}$ is the total electron generation rate, Δt is the model time step and R is a random number uniformly distributed between 0 and 1. It should be noted that as the probability of an electron being available at any given time period is relatively low (8) can be rewritten as

$$\dot{N}_{\mathrm{e}}\Delta t > R \tag{9}$$

using the Maclaurin series of the exponential function. Furthermore, provided Δt is sufficiently small compared to the period of the AC cycle the results will be independent of time step choice.

Earlier published work divides electron generation mechanisms into two groups, volume generation and surface emission; surface emission is then subdivided between metallic and dielectric surfaces [8]. The same approach shall be adopted in this discussion. The emission of charge from dielectric surface is assumed to be due to the detrapping of charge deployed from earlier discharge. Therefore for voids surrounded by dielectric material the seed electron for the very first PD must be generated by volume processes. For surface emission the discussion shall be restricted to electric fields with a magnitude below that which is required for Fowler-Nordheim emission which is reasonably for typical PD systems.

Volume Ionisation

Electrons may be generated in the air volume due to ionisation from background radiation. In [15] an expression for the electron generation rate due to this process is provided

$$\dot{N}_{\mathrm{e\ volume}} = C_{\mathrm{rad}}\Phi_{\mathrm{rad}}\rho V_{\mathrm{eff}} \tag{10}$$

where C_{rad} is a constant describing the absorption of radiation, Φ_{rad} is a constant describing the radiation density, ρ is the density of the air and V_{eff} is the effective volume of the void within which a free electron can develop into a PD. In [15] it is stated that "$C_{\mathrm{rad}}\Phi_{\mathrm{rad}}$ can be estimated from the atmospheric volume ionization rate 2×10^6 m^{-3} s^{-1} to be of the order $(C_{\mathrm{rad}}\Phi_{\mathrm{rad}})_{\mathrm{nat}} \sim 2 \times 10^6$ kg^{-1} s^{-1}." This calculation assumes that the density of air at atmospheric pressure is approximately 1 kg/m^3, which is perfectly reasonable. Unfortunately a reference is not provided to the atmospheric volume ionisation rate value of 2×10^6 kg^{-1} s^{-1}, so its origins are unclear. It is worth noting that differing values of the atmospheric volume ionisation rate have been reported in the literature, in some cases orders of magnitude higher than 2×10^6 m^{-3} s^{-1} [18]. However, it should be realised that the environmental conditions of some PD systems, such as the burial environment in underground high voltage cable, may influence the volume ionisation rate. In [3] $\dot{N}_{\mathrm{e\ volume}}$ is used to calculate the inception delay before the first PD for in a spherical void surrounded by a dielectric material, and reasonable agreement is observed between the theoretical prediction and experimental data. It should be noted that $\dot{N}_{\mathrm{e\ volume}}$ due to natural background radiation only (i.e. in the absence of radiation sources) is typically assumed to be relatively low and by itself it is unable to sustain PD activity at a significant rate.

Emission from Surface Charge on Dielectric Boundaries

For PD systems consisting of a void surrounded by a dielectric material it is possible for electrons to be generated due to the emission from surface charge deployed by earlier discharges. In [8] an equation is provided for this electron generation rate from dielectric surface, $\dot{N}_{\mathrm{e\ dielectric\ surface}}$, as follows

$$\dot{N}_{\mathrm{e\ dielectric\ surface}} = \nu_0 N_{\mathrm{dt}} \exp\left(\frac{-[\Phi - \Delta\Phi]}{k_{\mathrm{B}}T}\right) \tag{11}$$

where ν_0 is the fundamental phonon frequency of the material, N_{dt} is the detrappable charge population, k_{B} is the Boltzmann constant, T is the temperature, Φ is the work function of the surface and $\Delta\Phi$ is the lowering of the work function due to the electric field. This equation, or variations thereof [4, 7], have been widely used to capture the emission of charge from dielectric surfaces. However, where the equation originates from is unclear as an explicit reference is not provided. After a literature search it appears that it was originally derived from work conducted at King's College London in 1970's [19]. In this work researchers measured the current between two concentric tubes of Pyrex glass. The typical scenario considered in the paper is for the gap between the glass tubes to be a vacuum although different gases, in particular oxygen, were also considered. The glass tubes were filled with conducting liquids which were used as electrodes to apply an electric field through the glass tubes and the gap. In vacuum conditions emitting sites on the surface of the glass were observed visually, due to phosphor placed on the inner surface of the outer tube, under sufficiently high fields. The current between the cylinders was then measured at different applied voltages and temperatures to provide an estimate of the emission rate of electrons from the localised sites on the glass.

From the experimental data collected the authors formulate a theory for the emission of electrons from glass. It is argued that electron emission should be treated as a processes taking place at isolated sites where an electron impacting a barrier with a given frequency. Furthermore, the lowering of the energy required to overcome the barrier due to the electric field should be treated as the interaction between the emitted electron and a hole left of the surface. Thus the lowering of the work function, $\Delta\Phi$, is double the value used for metals. This means that for electron emission from dielectric surfaces,

$$\Delta\Phi = \sqrt{\frac{e^3 E}{\pi \varepsilon_0}} = 7.59 \times 10^{-5} E^{1/2} \text{ eV} \tag{12}$$

where E is the electric field, e is the electron charge and ε_0 is the permittivity of free space. Using the data of current against field the authors found that their expression for emission from dielectric surfaces was reasonable for electric fields above 5 kV/mm, however below the measured current was significantly lower than the estimated current. It is important to note that in much of the PD modelling literature, $\Delta\Phi$ is set to the value used for metallic surfaces which results in a different dependency on the electric field.

For charge deployed by a PD into a dielectric surface the emission characteristics may differ significantly from this investigation. Firstly, in the experimental work the emission was from bulk glass rather than from trapped charge within the dielectric close to the boundary. Furthermore, even if electron emission did follow this scaling, the experimental data was not in close agreement with it for fields below 5 kV/mm, which is still significantly above the inception field for a range of void sizes. The number of sites capable of emitting electrons is also a significant unknown. Typically N_{dt} is initially set to the total charge deployed by last PD, referred to as the physical charge, divided by the electron charge. In other words it is assumed that all of the trapped charge from the most recent PD is capable of emitting electrons immediately after the discharge. Between PD events it is assumed to undergo an exponential decay, the time constant of which is treated as a free parameter. The only justification for this appears to be that it allows the PD activity model to more closely fit experimental PRPD patterns, which is not completely valid given the existing uncertainties in the approach.

Emission from Metallic Boundaries

Emission from metallic surfaces is assumed to obey the Richardson-Schottky law

$$\dot{N}_{\text{e metallic surface}} = \frac{A}{e} C_{\text{th}} \mathrm{T}^2 \exp\left(\frac{-[\Phi - \Delta\Phi]}{k_{\text{B}} T}\right) \tag{13}$$

where A is the area of the emitting surface and C_{th} is a constant. For emission from metallic surfaces the lowering of the energy required to overcome the barrier due to the electric field should be treated as an interaction between the emitted electron and a corresponding image charge. This means that for electron emission from metallic surfaces,

$$\Delta\Phi = \sqrt{\frac{e^3 E}{4\pi \varepsilon_0}} = 3.79 \times 10^{-5} E^{1/2} \text{ eV.} \tag{14}$$

The Richardson-Schottky law is typically used to calculate current densities due to thermionic emission from metals in excess of 500°C and the work function of metals are typically above 3 eV. In order for any significant thermionic emission to occur at room temperature it is necessary to assume that the metal in fact has a much lower work function, between 1 and 1.5 eV. Fundamentally emission of charge from metallic surfaces into solid dielectric materials can occur at room temperature because charge distributions within thin films can be detected using space charge measurements [20]. Furthermore, there is evidence of emission obeying the Richardson Schottky law in capacitors at temperatures as low as 300 K, [21], although it must be noted that in this particular investigation the electric field strength was typically in excess of 100 kV/mm. It is also likely that this process is highly dependent on the properties of the interface, and for electron generation for PD the relevant boundary is between a metallic electrode and a gas. However, for a gas electrode interface at room temperature there does not appear to be conclusive evidence that there is electron emission obeying the Richardson-Schottky law.

Discussion

A critique of the main physical concepts typically used in PD activity models has been conducted. The review reveals that many of these concepts are based on work undertaken and reported in the 1960's and 1970's, which in some cases may not be applicable to PD systems. In this section a discussion is provided of the implications of these findings and possible developments moving forwards.

The results of this review show that while some of the physical concepts introduced in earlier work are still valid, they should be treated with caution. The inception field equation is derived from a system which differs significantly from typical PD systems, and the equations governing electron emission should really be interpreted as rough scaling laws. There is significant uncertainty in the validity of the concept that after a discharge the electric field within a void falls to a fixed residual value. A further point that should be addressed is that PD activity models typically require a large number of free parameters. As a minimum 3 free parameters are used: the work function of the void surface Φ, air pressure p and a time decay constant of N_{dt}. In [3] a scaling factor for electron emission from positively charge surfaces is introduced, primarily to allow the simulation to fit the experimentally observed "rabbit ear" PRPD patterns. If surface conductivity, which has not been discussed in this article, is also included it too is typically treated as a free parameter. Due to the large number of free parameters the fact that PD activity models can reproduce experimental data is not by itself validation of the physical concepts used. In [22] Heitz was able to reproduce a range of PD experimental data using a very simple model and adjusting the electron generation rate, inception field and residual field. In this work the approach was taken to try and describe physical processes using data analysis [23]. Such a method could be useful for analysing field data, where the model is fitted to the existing data and therefore allows changes in PD activity to be detected. However, it does not allow detailed insight into the physical mechanisms of PD activity.

Although more computationally costly, plasma dynamic simulations allow insight into the physical characteristics of the discharge itself to be considered. In particular surface charge density distributions and the apparent current pulses are emergent phenomena from the plasma dynamics. There is an established body of literature within the applied physics community and at present the overlap with the electrical engineering community is not as significant as it could be. Within the electrical engineering research community plasma dynamic simulations relating to PD have been performed, examples include work by: University of Bologna [24]. Chalmers University of Technology [25, 26], University of Southampton [17, 27], Ricerca Sul Sistema Energetico [28] and Xi'an Jiaotong University [29, 30]. Furthermore, although it is within the applied physics community, simulation work conducted by Babaeva *et al.* on discharges within bubbles, [31], is highly applicable to PD systems. Figure 1 is an example of output data, in this case the electric field distribution during a streamer propagation through a spherical air void, obtained using plasma dynamic simulations.

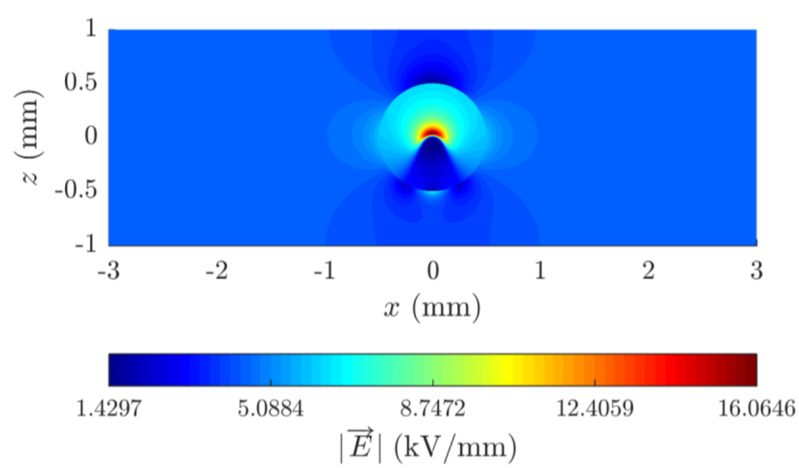

Figure 1: Electric field distribution during the propagation of a positive streamer through the axis a spherical air filled void embedded within epoxy resin. At the top of the simulation domain is a high voltage electrode set to 9 kV, the bottom of the simulation domain is grounded. The simulation work used to create this figure is provided in [17], the figure was created by mirroring an axisymmetric solution at the symmetry axis.

Experimentally measurements of surface charge density distributions using Pockel's cells have recently been used to investigate PD [30, 32, 33]. These measurements provide insight into the extent to which charge is deployed at the void boundary and also the movement and decay of charge on dielectric surfaces. Imaging of discharges within small voids in dielectric materials has not been widely attempted, although if a PD system was permissible to it extra information would be obtained, especially on the discharge paths taken through the void. Imaging of PDs in spherical voids embedded in epoxy resins was performed by Holbøll *et al.* in the early 1990's [34].

To summarise, there are a number of different avenues for future research into simulating PD. Future practitioners of PD activity simulations should be aware of the origins of the physical concepts in the models they are using and their limitations. Moving forwards, a deeper consideration of individual discharges, both through plasma dynamic simulations and advanced experimental techniques, are vital to improve understanding.

Conclusion

The intention of this article was to summarise the origins and provide a critique of the physical concepts used in PD activity models. The key points are:

1. The inception field equation, (1), can be expected to provide reasonable estimates of the electric field required for a PD to take place. However, it should be treated as an estimate rather than a physical law. This is primarily due to the experimental arrangement used to derive it, parallel plate electrodes with a separation greater than a centimetre will not necessarily have the same breakdown characteristics as voids less than a millimetre across surrounded by dielectric material.
2. The physical concept of a fixed residual field, the electric field in a void after a discharge, is questionable. It is certain that a PD will reduce the electric field within a void, but the extent of the reduction may depend on a number of factors including: the magnitude of the discharge itself and the surface charge at the void boundary. Pockel's cell measurements allow surface charge density distributions to be observed which allow the electric field after a discharge to be calculated. These experiments could be used to provide more insight into the residual field.
3. Electron generation mechanisms within air voids are still not fully understood. The equations provided for electron emission from dielectric and metallic surfaces appear reasonable, although moving forwards it seems advisable to adjust the work function lowering for dielectric surfaces based on the work conducted in [19]. It should be stressed that the equations should be treated as appropriate scaling laws which use free parameters such that they fit the experimental data. Fundamentally significant advances in understanding may be required for a rigorous description of electron emission for PD.

Researchers intending to develop new models of PD would be advised to read the supporting literature on the physics of discharges, in particular the historical experimental investigations cited in this article from the 1960's and 1970's, rather than simply beginning with the work from the 1990's. From a simulation perspective it would appear the plasma dynamic simulations could be a useful tool to inform PD activity models. Moving forwards more complex descriptions of the interactions between the plasma and the dielectric surfaces may be required especially after sustained PD activity. Experimentally Pockel's cell measurements and discharge imaging allow simulation work to be validated and provide physical insight into PD activity which cannot be made from PRPD patterns alone.

In conclusion, the physical concepts used in PD activity models should be treated with caution. Using plasma dynamic simulations and experimental techniques that allow the mechanism of the discharge itself to be investigated could offer valuable insight into PD activity. There is still significant scope for research work in the future where the ultimate aim is to provide a detailed physical interpretation of PD activity in operational high voltage plant.

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