On PD mechanisms at high temperature in voids included in an epoxy resin

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Abstract:
In this paper the effects of temperature on partial discharge (PD) activity taking place inside a spherical void in epoxy resin system are studied. Indeed, some experimental tests previously performed on specimens, having different void shapes, under multi-stress condition of temperature and voltage, have shown very different PD amplitude distributions at temperatures higher than ambient. However, this phenomenon cannot be explained only by taking into account the different thermobaric conditions of the enclosed gas. In consequence of the general physical inaccessibility of such voids, a study is here performed using a numerical model based on an evolutionary optimization algorithm. This is used to evaluate the range values for the physical parameters of the insulating system influencing the observed changes in PD activity. Finally, comments are presented about the adopted criteria by which the comparison between the experimental data and the simulated ones is performed, and about the interpretation of the dependence on temperature of the experimental PD.

SECTION I.Introduction
The necessity of higher and higher voltage levels in HV power systems has driven to a stronger demand of insulating materials with high electrical performances at affordable costs. Since synthetic polymers partially meet these requirements, they have been studied quite a bit in the most recent literature. However, they are affected by some aging problems also due to internal PD. These discharges take place in consequence of unavoidable local defects produced by the industrial manufacturing process, and promote local erosion of the material that may cause electric breakdown of the component in time. The difficulty of performing reliable life predictions and suitable evaluations of their reliability in presence of such degradation phenomena, hindered a wide diffusion of HV components made of epoxy materials.

Recently, computer aided techniques based on pulse height analysis or phase distribution analysis, have largely improved the possibilities of investigation in this field [1]– [4], thanks to their capability of recording and processing a large amount of data. Even though the information on the ‘ aging state’ of a system or on the incoming breakdown can be obtained now in many cases, the comparative analysis between materials in terms of resistance to PD activity can be improved further.

An intensive research activity on the subject has been carried out, covering many aspects of this phenomenon. In particular, two main research areas can be identified. The first area [5]– [9] uses modern digital measuring techniques in order to have some reliable indication regarding the kind of internal defects, which has been recognized by means of neural networks, and suitable numerical algorithms applied to the acquired data. The second one [10]–[12] develops a pioneering work on the physics of discharge, thus letting us know the basis to understand the discharge mechanisms and to improve the existing PD models.

Since many years, the authors have been studying the characteristics of PD activity in enclosed cavities at temperatures higher than the ambient, because some dielectric materials [13], [14], like the ones employed in electrical machines, are subjected in service to a condition where PD are found to be active under multistress conditions. On this subject, little information is available in the literature. In this paper a study on PD activity into an embedded spherical void at different working temperatures is presented. Starting from the current knowledge of PD physics, the temperature parameter T has been taken into account in all the equations describing the phenomenon. This dielectric configuration has been chosen because its electric field and PD activity is well known at 20°C, and because it is frequently encountered in insulation systems.

SECTION II.Some Physical Remarks on the Specimen

In order to characterize the insulating system dependence on the environmental temperature, it is necessary to know the electric field inside the void, the pressure during the initial stage of discharge activity, and the thermal characteristics of the epoxy resin.

A. Electric Field

Considering a spherical void of radius R, in the middle of a solid dielectric material between a couple of plane electrodes, it is known that the electric field distribution inside and outside the void can be evaluated solving the Laplace equation

$$\nabla^2 V=0 \quad (1)$$

where V is the scalar potential function. Equation (1) can be rewritten by spherical coordinates in a two-dimensional form

$$\frac{\partial}{\partial r}\left(r^2\frac{\partial V}{\partial r}\right)+\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\frac{\partial V}{\partial\theta}\right)=0 \quad (2)$$

where V is referred to as $V(r,\theta)$. Inside the cavity the solution is

$$V_i=-\frac{3\varepsilon}{\varepsilon_0+2\varepsilon}E_0 r\cos\theta \quad r<R \quad (3)$$

where ε_o and ε are respectively the absolute permittivity of the gas inside the void and of the surrounding dielectric, and E_0 is the electric field in absence of the void. The field inside the void along the main diametral axis ($\theta=0$) is

$$E_i=-\frac{\partial V}{\partial r}=\frac{3\varepsilon}{\varepsilon_0+2\varepsilon}E_0=f(T)E_0 \quad (4)$$

As can be noted in Equation (4), the temperature acts on the electric field through a function of the solid dielectric permittivity $\varepsilon(T)$, e.g. through the $f(T)$ parameter.

B. Making Test Specimens

Another parameter on which the related discharge activity depends is the pressure p inside the void, which is linked to the adopted manufacturing process for the specimen. In our case it is not possible to perform an exact measurement of p, but only a theoretical evaluation of it. The dielectric material used is an electrical graded epoxy resin (Bakelite GmbH: EA330 KA+KB), which is subjected to the following thermal cycle: curing at T1=353K for 6h and a post-curing at T2=403K for 15 h. Spherical defects have been produced artificially by injecting a defined quantity of dry air into the resin during its curing phase. At the beginning, the gas pressure in the void is considered to be 100 kPa because this phase takes place in an open vessel. After curing, the resin presented an estimated hardening shrinkage of ~3% (volume). Therefore, the ordinary gas equation can be expressed as

$p'_{T1}V'_{T1}=p''_{T1}V''_{T1}$ (5)
View SourceRight-click on figure for MathML and additional features.with V'_{T1} and V''_{T1}, p'_{T1} and p''_{T1} representing the volume and the pressure before and after the resin curing phase, and where $V''_{T1}=V'_{T1}/1.03$ from the above 3% shrinkage assumption. Therefore from Equation (5) it holds (in kPa)
$p''_{T1}=1.03p'_{T1}=103$ (6)
View SourceRight-click on figure for MathML and additional features.
During the post-curing phase the temperature is raised to 403K and has been kept constant for 15 h. As a result, the resin has a thermal expansion (from T1 to T2) which superimposes another shrinkage phase of ~1%. Therefore, the following equations can be written

$p''_{T1}V''_{T1}p'_{T2}V'_{T2}=nR_gT_1=nR_gT_2$ (7)
View SourceRight-click on figure for MathML and additional features.where n is the number of moles, $R_g=8.314510\ \mathrm{J mol^{-1} K^{-1}}$ is the universal gas constant, $V'_{T2}=V''_{T1}(1+3\sigma\Delta T)$ and $\sigma=30\times10^{-6}K$ is the thermal expansion coefficient of the resin. From the ratio between Equations (7) it follows that $p'_{T2}=118kPa$. The pressure value obtained at the end of the post-curing phase p''_{T2}, evaluated by the ordinary gas equations (written at constant temperature) and roughly considering that $V''_{T2}=V'_{T2}/1.01$, is $p''_{T2}=119$ kPa.
Bringing the cooling process down to 293K(T0) and considering that $V''_{T2}=V_{T0}(1+3\sigma\Delta T)$, it is possible to get $p_{T0}=87kPa$. In a similar way at T1 it resulted in $p_{T1}=104kPa$. Observe that, even if the volume cavity may be considered constant between T0 and T1, the related pressure changes of only 10 to 15%.

C. Thermal Characteristics of The Resin

In order to set the thermal environmental conditions for the study of PD activity and to obtain the f(T) curve in Equation (4), the knowledge of ε(T) at 50 Hz is required. But, the difficulty of obtaining experimentally such curve is well known because the 50 Hz frequency is also the power frequency and the results could be corrupted by an high interference noise level coming from the feeding instrumentation used. For this reason the resin permittivity dependence on temperature was investigated in a set of five frequencies (from 400 Hz up to 1 MHz) and then the results were extrapolated at 50 Hz. In this aim a sheet specimen (1 mm thickness) has been put into a three-electrode holder where, in order to avoid any influence of atmospheric moisture, a low pressure (~50 Pa) condition was induced. A computer controlled and automatic precision bridge was used to get ε_r measurements in the above frequency range and temperature going from the ambient up to 120°C with an heating specimen rate of ~1∘C/min. The results reported in Figure 1 show a very negligible effect of temperature on permittivity, so that the f(T) function has been assumed constant in practice and equal to 1.32 in the range of our interest.

Figure 1. - ε_{r} as function of temperature at constant frequency.
Figure 1.
ε_r as function of temperature at constant frequency.

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D. Surface Conductivity of the Resin

Another parameter, on which PD depends, is the wall surface conductivity of the enclosed void. Indeed the discharge activity produces many gaseous byproducts that attack the resin surface in consequence of their chemical nature. This consequently changes the surface conductivity of the resin. A virgin epoxy specimen, e.g. not subjected to discharges, generally presents a surface conductivity k_s of about 10^{-18} or $10^{-16}\ \Omega^{-1}$. Bartnikas et al. [12] have experimentally observed that epoxy surfaces of plane shape directly exposed to PD in uniform electric field undergo important chemical and physical modifications; for instance a strong increase of the surface conductivity from 10^{-16} to ~10^{-10} has been found. This important increase was observed to happen during the first 100 h of exposure to PD, then k_s appeared to go toward a saturation level. On the other hand Ku-Liepins [15] observed that when the temperature of a resin increases from 20 to 150°C, the surface conductivity goes up to $10^{-4}\ \Omega^{-1}$.

However, in the case of a spherical void, some further useful aspects should be pointed out. For instance not all the areas of surface cavity are equally attacked by discharges, e.g. a more complex mechanism due to surface conductivity should be observed. Actually, the void surface sections parallel to the electric field are less, and differently, eroded than the areas which are hit perpendicularly by the discharges, as shown in Figure 2 where the evolution of a generic discharge is depicted. Therefore, a surface conductivity causing a sensible PD charge decay would be effective only if it is active along the equatorial area of the void, e.g. parallel to the PD current flow. This surface is not bombarded by charge carriers and therefore can remain non-conducting during the tests. It is this surface conductivity which we will refer to by the ks symbol. Considering that in this experimental work the tests have been performed at 20 and at 80°C and that aging phenomena can be ignored during their execution, a reasonable assumption for the related change of the resin conductivity due to temperature increase has been set to ~2 orders of magnitude starting from $10^{-18}\ \Omega^{-1}$ that was assumed at 20°C from the resin data sheet.

Figure 2. - Spherical void in a generic discharge condition.
Figure 2.
Spherical void in a generic discharge condition.

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SECTION III.The Pd Model
The basic physical principles upon which the PD model is built, are known from the literature [16], [17]. Many types of discharge can generally occur in epoxy embedded voids [18], They are streamer discharges, Townsend discharges, swarming partial microdischarges, and glow discharges.

They are distinguished by their charge magnitude and current shape signals [19]. In this work the study is restricted only to the experimentally detected pulsive discharges (streamer), which are associated with higher pulsive-shape currents and detectable by conventional PD detector systems. Other discharges usually produce a much lower charge, or are pulseless. Furthermore, in most cases, it has been found that they are active during the aging progression of a void [20].

On the basis of Equation (4) the field inside the cavity of radius R is

$$E=fE_0+\frac{q}{\pi r_1^2}\frac{1}{\varepsilon_0}\tag{8}$$

View SourceRight-click on figure for MathML and additional features.where ±q is the charge deposited on the cavity polar area (having r_1 mean radius, obviously lower than R) by previous PD activity in the ac steady state, as shown in Figure 2.
It is accepted that the inception field E_i to produce a streamer discharge within a spherical void has to exceed the value [21]

$$E_i\geq p\left(\frac{E}{p}\right)_{cr}\left(1+\frac{B}{(p2R)^n}\right)\tag{9}$$

View SourceRight-click on figure for MathML and additional features.
In the last equation, $(E/p)_{cr}=24.2 (\mathrm{V\ Pa^{-1}m^{-1}})$ e.g. the value of E/p for which the effective coefficient of ionization η is zero, $B=8.6\ (\mathrm{Pa\ (m)})^{0.5}, n=0.5$ (characteristic properties of the included air at constant temperature), while the residual value of the electric field E_r in the cavity after a discharge is here assumed equal to $\gamma(E/p)_{cr}p$ with $\gamma=0.2$ [17]. Therefore, once the condition given by Equation (9) is fulfilled, a starting electron is need for triggering the multiplication avalanche mechanism. This electron availability has a random nature, thus the ensuing PD phenomenon results in its classical statistical time evolution. Our experience in the tests performed at 20°C was very similar to the one of other authors [17]: when discharges were ignited by natural radiation after a relatively long inception delay, then they continued involving a mechanism practically controlled by surface charge de-trapping emission.

When the test temperature was elevated to 80°C (as a hypothetical consequence of the real working condition for the dielectric material), the enclosed void was subjected to a transformation at constant volume, e.g. the gas density remained constant while the inside pressure increased as a consequence of the increased kinetic energy of the gas molecules. In principle, this should give the same and identical discharge mechanism as at 20°C, but in the experiments carried out and here presented, the inception discharge voltage resulted at $80^{\circ}\mathrm{C}\sim 40\%$ higher than at 20°C and in all the specimens, PD presented a sort of intermittency. This fact has been assumed as indicative of a different phenomenon taking place at 80°C and, following the classical discharge. theory, the increase of pressure does not seem to be as the only important cause. However, on the basis of the results obtained at the end of Section 2.2. $(E/p)_{cr}$ has been assumed constant in Equation (9) within the examined temperatures, while the evaluated increase of p has been reported on the Ei value. Furthermore, the PD activity has been measured without an external X-ray source, that is in natural conditions, and subjecting a virgin specimen to 20 kV, 50 Hz constant voltage until discharges appeared. Then it was left under this voltage for a further 4 h to let discharging phenomenon go to the steady state condition, and thus the discharge inception voltage was measured in agreement with the IEC-Standard No. 270, 1981.

The charge q in Equation (8) is not a constant quantity, but it mainly changes because of the transferred charge Δq due to the previous dis- charge:

Δq=εoπr21(E−Er)(10)
View SourceRight-click on figure for MathML and additional features.Secondly a further change, which q(t) is subjected to, can be due to charge surface conduction along the equatorial area of wall cavity, according to Ohm's law
−dqdt=G(T)Ed(11)
View SourceRight-click on figure for MathML and additional features.where G(T) is the surface conductance of the resin as a function of temperature. In particular, G(T) can be expressed approximately as function of the specific surface conductivity k,
G(T)=ks(T)2πr1d(12)
View SourceRight-click on figure for MathML and additional features.where d is the mean distance, in the electric field direction, between the two polar areas of the void where the discharge is taking place. It has been assumed that the hypothetical conducting surface is the mantle of the equivalent cylinder of d height as represented in Figure 2.
After the PD activity has been started, a main source of initial electrons became the surface emission mechanism of the charges deployed on the void surface. However, at the moment the surface emission phenomenon in PD working conditions is not sufficiently understood in its physical mechanism. Therefore, let us consider the number of trapped electrons

Ne=q(t)e(13)
View SourceRight-click on figure for MathML and additional features.where e is the elementary charge. Part of the Ne electrons released on the void surface diffuse into energetically deeper traps and/or into depth of the insulating material from where they are no more extractable. To consider this loss from a phenomenological point of view, the surviving electrons could be modeled roughly by an exponential decay term exp −(t/τtr) with a time constant τtr representing an effective lifetime of the electrons in an extractable trap. Furthermore, these electrons are supposed to be thermally de-trapped and then emitted from the surface on the basis of the ϕtr function value, which is
ϕtr=ϕ−eE4πε0−−−−−√(14)
View SourceRight-click on figure for MathML and additional features.where ϕ is the de-trapping work function of the material expressed in eV. This should give a surface de-trapping rate
Ns=Neexp(−tτtr)v0exp(−ϕtrKT)(15)
View SourceRight-click on figure for MathML and additional features.where v0 is the fundamental phonon frequency of the material, K the Boltzmann constant (8.617385×10−5 eV K−1) and T the absolute temperature. If one wishes also to consider the production of electrons coming out from the natural radiation phenomenon, that is supposed to be always present, then the following should be taken into account
Nr=CrΦr(ρp)0p(πR3)(1−μ−0.5)(16)
View SourceRight-click on figure for MathML and additional features.where CrΦr=2×106kg−1s−1, (ρ/p)0=10−5kg m−3Pa−1 is the pressure reduced gas density and μ is the ratio between the applied voltage and the streamer inception voltage derived from Equation (9). Therefore, the total rate production of electrons ready to trigger a discharge becomes
Nt=Ns+Nr(17)
View SourceRight-click on figure for MathML and additional features.
In order to consider the statistical aspect of PD, a new probability function for the occurrence of a discharge has been defined here as

P(dt)=∑1=impi[1−exp{−(Ntdtαi)βi}](18)
View SourceRight-click on figure for MathML and additional features.where m is the number of elementary Weibull functions fitting the experimental data and αi and βi their parameters. In our experimental work, it resulted in m=2 for 20°C and m=1 for 80°C. This probability function has been chosen because it has better capability (by means of α and β parameters) to reproduce the observed different statistical aspects of PD at 20 and 80°C. Therefore, in the time interval dt, if the previous condition of Equation (9) is fulfilled, then Equation (18) is evaluated and compared with a random

generator's output. If this number is smaller than P (dt), then the electron is assumed to trigger the discharge.
Direct comparisons between the simulated data and the experimental ones have been performed by evaluating the apparent charge Δq′ induced at the electrodes by each true charge Δq given by Equation (10) in agreement to the relation [16]

$\Delta q' = \Delta q g 2R \nabla \lambda 0$ (19)
View SourceRight-click on figure for MathML and additional features.where, for a spherical void of diameter 2R,$g=2\varepsilon r/(1+2\varepsilon r)$ and $\nabla\lambda 0$ is the gradient of the dimensionless scalar field function λ0 [21], which characterizes the coupling of the defect location to the measuring electrodes.
SECTION IV.Experimental Test
To study the temperature effect on PD activity, many specimens have been made with void diameters ranging from 1.3 to 2 mm but with constant inter-electrode resin thickness equal to 3.5 mm.

All tests have been performed in agreement with a well defined procedure, either at 20°C or at 80°C, following the steps as below reported:

select the temperature to use in PD tests, 20 or 80°C

subject the specimen to 50 Hz sinusoidal voltage of 20 kV until discharge activity starts

leave the specimen under the second condition for 4 h to be sure PD activity is in steady state conditions

measure PD inception voltage

start with PD measurements after the specimen has been left for at least 5 min at the test voltage, that was chosen between 10 and 32 kV.

A digital instrument [8] have been used in the experiments. This is able to produce and store in computer memory two data vectors, the first related to the amplitude discharges, the second to the corresponding phase angles of the test voltage. The selected acquisition time was 30 s. Thus, a suitable elaboration software outputs the following diagrams:

H(q,n) amplitude histogram, as number of discharges n vs. discharge amplitudes q (positive and negative);

H(φ,qm) charge-phase histogram, as the mean charge value qm vs. the ignition phase of test voltager, φi.

H(φ,n) phase histogram, as number of discharges n vs. the ignition phase of test voltage φi.

However, a three-dimensional representation of the above data is often required in terms of H(φ,q,n) distribution.

In Figures 3 and 4, some measurements made at 20°C are reported. The tests have been performed either on a specimen having a 2 mm diameter cavity with voltages ranging from 12 kV (discharge inception voltage) to 32 kV or on specimens with different cavity diameter, but at constant voltage of 20 kV. In this case, only positive discharges have been reported since the negative ones resulted almost symmetrical to the former. The discharge activity can be considered as the combination of two groups of discharges, the first one made of a large number of discharges having almost the same amplitude and the second one of a small number of discharges with higher amplitudes. Their disposition within the voltage period is clearly shown in Figure 5, where a three-dimensional PD Pattern for a specimen subjected to 28 kV having an embedded void with 1.8 mm diameter, is reported. In particular, the second group of discharges (higher amplitude discharges with lower repetition rate) is concentrated in the area of the sign inversion of the electric field.

Figure 3. - Amplitude histograms of positive discharges from 12 to 32 kV of a 2 mm spherical void at 20oC.
Figure 3.
Amplitude histograms of positive discharges from 12 to 32 kV of a 2 mm spherical void at 20oC.

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Figure 4. - Amplitude histograms of positive discharges at 20 kV for different void diameters at 20oC.
Figure 4.
Amplitude histograms of positive discharges at 20 kV for different void diameters at 20oC.

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Figure 5. - An experimental 3d histogram of PD in a 1.8 mm spherical void at 28 kV and 20oC.
Figure 5.
An experimental 3d histogram of PD in a 1.8 mm spherical void at 28 kV and 20oC.

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The tests performed at 80°C show a discharge mechanism quite different with respect to 20°C, as is seen in Figure 6 where two measurements at 20 and 80°C are reported for direct comparison purposes. Furthermore, the range between the minimum (q_{min}) and the maximum value (q_{max}) of detected discharges becomes at 80°C much larger than at 20°C, and a lower and lower discharge repetition rate is observed. The peak shaped histogram of the amplitude discharges is no more present and the pulse charge magnitudes are randomly. distributed within the q_{min}, q_{max} interval. The 3d PD pattern histogram has consequently changed, as Figure 7 shows the case of a 1.8 mm diameter void, and the discharges have now a completely different amplitude and phase distributions. Furthermore, the ratio between the discharge number in a voltage period at 20 and at 80°C became ~10, e.g. one is stressed to believe that at 80°C the electron availability inside the void becomes drastically reduced.

Figure 6. - Direct comparison between discharges at 20 and at 80oC in a 2 mm void at 26 kV.
Figure 6.
Direct comparison between discharges at 20 and at 80oC in a 2 mm void at 26 kV.

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Figure 7. - An experimental 3d histogram of PD in a 1.8 mm spherical void at 28 kV and 80oC.
Figure 7.
An experimental 3d histogram of PD in a 1.8 mm spherical void at 28 kV and 80oC.

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SECTION V.Interpretation of 80°C PD Data by a Numerical Model

On the basis of what reported in the previous Section, a model of PD activity has been attempted first at 20°C, and afterwards at 80°C by a program written (Visual C++) in our laboratory. While the pressure p inside the cavity and the resin surface conductivity k_s are easily identifiable either from a numerical point of view and from their dependence on temperature (see Sections 2.2 and 2.4), the others parameters entering the model via Equation (15) can be identified in τ_{tr} and in the exponential term $v_o \exp(-\phi/KT)$ that as a whole can be called $C(T)$.

The software used for evaluating τ_{tr} and $C(T)$ parameters was derived from the differential evolution (DE) algorithm described in [22]. It can be categorized into a class of evolutionary optimization algorithms, comprising genetic algorithms and evolution strategies. Like any other evolution process in nature, DE maintains a population of alternative solutions for the optimization problem to be solved. These alternative solutions are individuals. of the population, from which the population of the next generation is created using a specific reproduction scheme. A cost function, used for evaluating individual solutions, is minimized comparing the Weibull distribution obtained from the experimental test with the same distribution output by the numerical PD model. Obviously, individual solutions with a low cost function value have higher probability to survive to the next generation than the individuals with a high value. The parameters found by the program are of course not the exact mathematical solution of the problem (which we do not know) so to get some rigorous physical interpretation of the phenomenon but, knowing their related range values from the heuristic knowledge of the phenomenon and following the idea of finding model parameters that are physically reasonable in describing the experimental data, we deemed they could be defined as good parameters for our purpose. Furthermore, in consequence of the random nature of PD, a statistical analysis has been performed on the solutions found by the numerical model to check their compatibility with the experimental data. Once the simulation was performed at

20°C, the main authors goal in this research was to find the change direction (increase or decrease) to which the τ_{tr} and C(T) parameters are to be submitted to in order to have a possible simulation of the PD activity occurring at 80°C. Finally, a sensitivity analysis on the parameters of the solutions here presented has been added.

After [23] it has been found that for polymers, typical values for vo are of the order of 1012 to 1014 Hz, while a range of 0.5 to 1.8 eV has been assumed for the work function of the resin. Consequently, C(T) was defined in the range to be inspected. An oriented strategy must be followed for the choice of the τ_{tr} range. Actually, τ_{tr} has been supposed to be within 1 and 10 ms at 20°C [16], [17], while at 80°C an higher and higher value, to 1000s, has been hypothesized in agreement to what showed in [17] for some experimental and simulated life tests performed on specimens similar to those ones here reported. Currently, it is not possible to give a precise and physical explanation about this very high value, since τ_{tr} is essentially a phenomenological parameter, but the related results here reported are quite in agreement with this increase tendency.

The numerical model simulates a PD activity along 30 s in a geometrically and physically defined specimen giving as output two arrays, the first one related to the pulse discharge amplitudes and the second one related to the corresponding phase angles of the test voltage. As already said, to each found solution a statistical filter has been applied.

On the basis of the results presented in literature [24], it can be argued that statistical analysis of PD data can give useful information because thousand of data can be compressed into simple numbers easier to be manipulated. In particular, to represent the shape profile of a discrete distribution $y_i=f(x_i)$ it is widely accepted the use of the Skewness (Sk) and Kurtosis (Ku) parameters. More precisely, they are the third and the fourth moments of $f(x_i)$, defined as

$$Sk=\frac{\sum_{i=1}^{n}(x_i-m')^3 f(x_i)}{\sigma^3\sum_{i=1}^{n}f(x_i)} \qquad Ku=\frac{\sum_{i=1}^{n}(x_i-m')^4 f(x_i)}{\sigma^4\sum_{i=1}^{n}f(x_i)}-3 \qquad (20)(21)$$

View SourceRight-click on figure for MathML and additional features.where m′ and σ are the average value and the standard deviation of $f(x_i)$ respectively. Others parameters that have been taken into account are: the PD average discharge current, defined as [25]

$$I_{PD}=\frac{\sum|q_i|}{\Delta T} \qquad (22)$$

View SourceRight-click on figure for MathML and additional features.with ΔT the acquisition time, and the voltage discharge phase range for positive discharges $\Delta\varphi_{\circ}(+)$ and for negative ones $\Delta\varphi_{\circ}(-)$, and the discharge number acquired in 30 s.

The above parameters have been evaluated for the PD patterns obtained from measurements performed on a sample of five identical specimens at 20 and 80°C under different voltage levels and with void diameters ranging from 1.7 to 1.9 mm, optically checked.

In Table 1, the scatter range experimentally found at 20°C for each of the above parameters is reported in the second, fourth and sixth column. In the third, fifth and seventh column the results obtained from the one of the simulated tests which has the higher percentage of statistical parameters entering within the related experimental ranges are reported. The hypothetical void diameter was 1.8 mm and the simulation has been performed for 30 s under 28 kV. In Figure 8 the related 3d pattern together to the values of the parameters τ_{tr} and $C(20^{\circ}C)$ found by the DE algorithm are reported. It should be noted that Sk and Ku parameters have been evaluated on three distributions, e.g. $H(q,n)$, $H(\varphi,q_m)$ and $H(\varphi,n)$. A global analysis of the data puts into evidence a fit of the simulation, that could be considered good since ~70% of the related parameters are falling into the corresponding scatter range of the experimental data, and only a few of them are close to the scatter range limit. In particular two of them, e.g. the kurtosis parameter applied to $H(\varphi,n)$ for positive and negative discharges, are out of range. However, it is well known that the skewness parameter in most cases specifies better than what the kurtosis does, the characteristic profile of a distribution shape.

Figure 8. - An example of simulated 3d histogram of a 1.8 mm spherical void at 28 kV and 20°C. Simulation obtained for: $C(20{\rm T})=4.50 E05 Hz, \tau_{\rm tr}=0.009_{\llcorner}$. The fixed parameters are ${\rm k}_{s}=10^{-18}\ \Omega$−1 and $p=87{\rm kt}^{1}{\rm a}$

Figure 8.

An example of simulated 3d histogram of a 1.8 mm spherical void at 28 kV and 20°C. Simulation obtained for: $C(20T)=4.50E05 Hz, \tau_{tr}=0.009 \llcorner$. The fixed parameters are $k_s=10^{-18}\ \Omega^{-1}$ and $p=87kt^1a$

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Table 1. Comparison between experimental and the simulated PD data at 20°C reported in Figure 8
Table 1.- Comparison between experimental and the simulated PD data at 20°C reported in Figure 8
Table 2. Comparison between experimental and the simulated PD data at 80°C reported in Figure 9
Table 2.- Comparison between experimental and the simulated PD data at 80°C reported in Figure 9
Following the same procedure, the next step has been to attempt an evaluation of the previously described parameters in a PD test simulated at 80°C. In Figure 9 and in Table 2 the related results are reported for a void with the same 1.8 mm diameter. Again, as at 20°C, except for the two kurtosis parameters applied to H(φ,n) distribution, the very slight differences of some other ones are surely due to some approximations contained inside the model equations.

Figure 9. - An example of simulated 3d histogram of a 1.8 mm spherical void at 28 kV and 80°C. Simulation obtained for: $C(80^{\circ}{\rm C})=2.30 E09 Hz, \tau_{\rm tr}=600{\rm s}$, The fixed parameters are ${\rm k}_{s}=10^{-16}\ \Omega^{-1}$ and $p=104{\rm kPa}$
Figure 9.
An example of simulated 3d histogram of a 1.8 mm spherical void at 28 kV and 80°C. Simulation obtained for: $C(80{\circ}C)=2.30E09Hz,\tau tr=600s$, The fixed parameters are $ks=10-16\ \Omega-1$ and $p=104kPa$

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A sensitivity analysis of the 80°C simulation on the single model parameter values have been performed in order to study the incidence of their values on the solution presented in Figure 9. In particular, the role of the charge decay time constant τtr has been explored by changing its value starting from the presented value of ~600s and leaving the other parameter unchanged. The results are reported in Figure 10 in a bidimensional plot as the mean charge versus the voltage inception phase. It is possible to see that only a τtr of the order of 30 ms produces strong changes in the simulation, intermediate values have a little effect except for the discharge number that shows a little decrease, thus giving a range of acceptable τtr value between 1 and 1000 s and surely not overlapping over the one related at 20°C. On the contrary, starting again from the conditions outlined in Figure 10(a) it is sufficient to change the C (80°C) value from (2.30 E-09 Hz) to (2.30 E-07 Hz) for having a very strong different discharge activity as reported in Figure 11.

Figure 10. - Effect of $\tau_{\rm tr}$ value on the simulation presented in Figure 9. (a) $\tau_{\rm tr}=600\Vert$, discharge number in 30 ${\rm s}n=3214$ (b) $\tau_{\rm tr}=10$ s, discharge number in $30 {\rm s}n=2986$. (c) $\tau_{\rm tr}=1{\rm s}$ discharge number in $30 {\rm s}n=2714$ (d) $\tau_{\rm tr}=0.03{\rm s}$ discharge number in $30 {\rm s}n=1234$.
Figure 10.
Effect of τtr value on the simulation presented in Figure 9. (a) $\tau tr=600 \Vert$, discharge number in 30 sn=3214 (b) τtr=10 s, discharge number in 30sn=2986. (c) τtr=1s discharge number in 30sn=2714 (d) τtr=0.03s discharge number in 30sn=1234.

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Figure 11. - Effect of C(T) value on the simulation presented in Figure 9. $C(80^{\circ}{\rm C})=2.30 E-07 {\rm R}$ and discharge number in $30 {\rm s}n=18134$.
Figure 11.
Effect of C(T) value on the simulation presented in Figure 9. $C(80{\circ}C)=2.30E-07R$ and discharge number in 30sn=18134.

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The first consideration that can be put forward concerns the decrease of C(T) when the temperature goes from 20 to 80°C. It is not possible to obtain from the C(T) value here found, an unique couple of vo and ϕ related values. This concept is shown in Figure 12 where ϕ is reported vs. vo for $C(20{\circ}C)=4.50$ E-05 Hz and $C(80cC)=2.30E-09H2$. In every case it is clear that for the same range of vo values, different and not overlapping ranges for ϕ values are shown. In particular higher ϕ values than at 20°C are present at 80°C. Furthermore, a slight inter- dependence of the above increase tendency in order to reproduce the experimental PD data at 80°C, could appear sound, because the stronger binding (ϕ increase) of the electrons may also explain the increased decay time to be assigned to τtr. This fact should let us suppose that the main difference of PD activity at temperature higher than the ambient may be a higher discharge time lag and consequently a higher discharge overvoltage, thus producing a strong decrease of the discharge number and their spread over a larger and larger interval between qmin and qmax.

Figure 12. - Plot of the function $v_{0}\exp(-{\phi\over KT})= C(T)$ for $C (20^{\circ}{\rm C})=4.50{\rm E}\rightarrow 05 Hz$ and for $C(80^{\circ})=2.30 ti-09 {\rm H}_{d}^{\prime}$.
Figure 12.
Plot of the function v0exp(−ϕKT)=C(T) for C(20∘C)=4.50E→05Hz and for C(80∘)=2.30ti−09H′d.

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This interpretation of the results related to the effect of temperature on PD activity could be very near to the evolution of the experimentally observed phenomena, that was also present with similar characteristics in different cavity shapes [20].

Finally, the authors wish to point out that what was reported in this paper concerns voids not subjected to PD aging phenomena. In fact as already said in Section 2.4, the protracted exposition of a resin surface to the acid gaseous products of discharges changes the PD pulse sequence during the aging in a way that is in general not known in depth. However, we deemed it very interesting to have a good and reasonable knowledge of the starting PD activity, especially when the temperature is also present as a parameter conditioning the internal discharges.

SECTION VI.Conclusions

IN this paper a study of PD activity at 20 and 80°C in spherical voids is presented. Starting from the consideration that such voids are always inaccessible, this study has been performed simulating the PD activity and then extracting the proposed solution from the ones found by the algorithm by means of an analysis based on the comparison of sixteen statistical parameters. The interpretation of what happens at 80°C in PD activity can be read through the changes which the model parameters are subjected to for a good fit.

The following observations can therefore be made.

From the experimental tests here performed on PD in an embedded void inside epoxy material, we have observed that discharge activity strongly changes from 20 to 80°C. The range between the q_{min} and the q_{max} value of detected discharges becomes at 80°C much larger than the one at 20°C and the ratio between the discharge number in a voltage period at 80°C and amounted of ~10. Therefore, one is stressed to believe that at 80°C the electron availability inside the void becomes drastically reduced.

The simulation function C, depending on the material work function ϕ and on v_0 value, decreases from 20 to 80°C, and from its analysis at constant temperature it appears that within the expected range of values for v_0 it is likely that ϕ increases with temperature, thus giving a lower first electron availability for the discharges. This fact can. produce an increase of the discharge time lag and a strong reduction of discharge rate.

At 80°C it is necessary to increase the time constant τ_{tr} value. This may mean a higher lifetime of charges deposited on the void polar area and could be proposed as an effect of ϕ increase, e.g. a higher work to extract an electron from the material surface with a consequent lower first electron availability.