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A Townsend’s secondary ionization coefficient estimation method for partial discharge inception voltage prediction for insulating polymers

Y. Kemari1,2, C. Van de Steen1, G. Belijar1, L. Laudebat2, S. Diaham2, Z. Valdez-Nava2 and C. Abadie1
1IRT Antoine de Saint Exupéry, 3 Rue Tarfaya, CS 34436, Toulouse cedex 4, France.
2LAPLACE (Laboratoire Plasma et Conversion d’Énergie), Université de Toulouse, CNRS; Bat 3R3, 118 route de Narbonne, F-31062 Toulouse cedex 9, France.
youcef.kemari@irt-saintexupery.com kemari@laplace.univ-tlse.fr

Abstract- Paschen’s law established from Townsend’s theory has been widely used to compute partial discharges inception voltage (PDIV) in electrical insulation systems (EIS) using numerical models. The accuracy of PDIV calculation depends on a number of parameters such as the Townsend’s secondary ionization coefficient γ. The present paper aims to propose a straightforward way to obtain a first estimation of γ by combining PDIV measurements and a robust experimental-simulation approach that has been presented in a previous work to predict PDIV for aeronautical applications. In this paper, a needle-plane configuration is adopted for PDIV measurements and modeling in the case of two insulating films; a polyimide (PI) and a polytetrafluoroethylene (PTFE). The estimated value of γ is determined as the value that provides the best fit with PDIV measurements for each material at 20 °C. The estimated values of γ at 20 °C are 6.5x10⁻⁴ and 10⁻⁴ for PI and PTFE respectively, which are much lower than the traditional value found in the literature for metallic electrodes (10⁻²). Moreover, the temperature dependence of γ is investigated from 20 up to 200 °C at an atmospheric pressure of about 1 atm. It is found that the use of the literature value could lead to an error of about 30% between simulated and measured PDIV values.

Keywords: partial discharges inception voltage, Townsend’s secondary ionization coefficient, finite element simulation, polyimide, PTFE.

I. INTRODUCTION

In a context of increasing voltage for hybrid or electric aircraft propulsion, partial discharge (PD) inception voltage (PDIV) is a key indicator when designing electrical systems. For this, accurate models for PDIV estimation are needed to design the EIS [1, 2]. However, the accuracy of PDIV calculation depends on different variables and parameters, among them, the Townsend’s secondary emission coefficient γ [2-4].

In the Townsend’s mechanism for metallic plane electrodes separated by air, the γ coefficient represents the ratio of the number of electrons issued from the cathode, and which participate to the electronic avalanche, over the number of ions bombarding the cathode.

This coefficient depends on many parameters such as the electric field, the gas composition and the electrodes material [2-4]. The common value of γ found in the literature is 10⁻² [5]. However, this coefficient remains not well known in the case of insulating polymers [2, 3].

For the aim to predict PDIV in electrical motors using a motorette model, P. Rain et al. [6] claimed to have determined a value of γ = 4x10⁻⁴ by experimental measurements at Renault laboratory for enameled magnet wires separated and enclosed by an insulating paper. Although, the used experimental method was not given in the paper. On the other hand, P. Collin et al. [3] proposed an experimental study coupled with a 2D-FEM to determine the secondary electron coefficient values in the case of two parallel enameled round wires for three different polymers under normal temperature and pressure conditions (23 °C, 1 bar). However, the dielectric constant was considered equal for all samples. The authors of [3] found that the estimated values of γ are more than 10 times lower than the most common value γ=10⁻². This coefficient was quite constant for copper diameters ranging from 0.5 to 1 mm wires with a polyamide-imide (PAI) overcoat. Quite a different approach was followed by M. Gómez de la Calle et al. [2] combining Paschen’s law in gases with FEM to predict PDIV in a twisted pair of enameled magnet wires geometry using constant-field lines in turn-to-turn insulation systems. The authors have also focused a part of their work to evaluate the uncertainty of PDIV prediction due to a poor estimation of γ. The gamma value found in [2] for the epoxy resin was 7.8x10⁻⁴ at 25 °C. Besides, it can be found in many models existing in the literature [4, 7] that the value γ=10⁻² has been widely used by some researchers to predict PDIV in EIS with insulating polymers. In many cases, this can affect the accuracy of the PDIV estimation, which could lead to a suboptimal insulation system and overweight or unreliability. In this paper, we investigate the influence of the secondary emission coefficient of Townsend γ value on the quality of PDIV prediction. For this, we propose a straightforward method to give a first estimation of a “macroscopic” γ, which represents the effective emission from the cathode resulting from different mechanisms [5] for a needle-plane configuration in the presence of a single insulation layer of PI or PTFE placed between electrodes. This method, developed in the framework of HYBELEC project at IRT Saint Exupéry, is based on a robust experimental-simulation approach that has been presented in a previous work [8] to calculate PDIV where insulating material properties are defined in simulations.
from extensive dielectric spectroscopy measurements. Moreover, the temperature dependence of $\gamma$ will be investigated for each material.

II. EXPERIMENTAL

A. Materials and Samples Preparation

The studied insulating materials in this paper are PI, under the trade name Kapton FN®, and PTFE, both are intended for power aeronautic cables. Samples of each material were provided in the form of films with a thickness of 30 and 225 µm for PI and PTFE respectively. Sintering of PTFE was performed in the laboratory in an oven at 360 °C for 10 min in order to obtain samples representative of the material used in the cable. The sintered PTFE sample has a final thickness of 210 µm. Finally, 3 x 3 cm² samples were cut for each material for PDIV measurements.

B. PDIV Measurements

After being dried at 100 °C for 48 h, a 30 nm-thick gold layer was deposited on one side of each sample in order to avoid air gaps between the plane electrode and the material. The tested sample was mounted on the grounded flat electrode of the test cell. Then, the tip of the needle electrode, with an edge curvature radius of 1 mm, was let vertically free and in contact with the top of the material. The test cell was placed in an oven that can span from 20 to 200 °C and the air pressure is controlled and stabilized at ambient pressure of about 1 atm. Negative temperatures are not investigated in this work since it requires to modify the gas composition. Also, high temperatures are more likely to lead to electron emission [2].

A 50 Hz voltage was applied to the needle by a HV amplifier (Trek model 10/40A-HS) associated to an arbitrary waveform generator (AFG 3022C) as shown in Fig. 1. For PD detection, two non-intrusive sensors were placed on the cable connected between the test cell and the ground: a Jack-SMA connector with a capacitive effect and a wide band fast current transformer (Bergoz FCT-016-1.25, France). The acquisition tool used is an oscilloscope (Keysight DSOS204A, France) with a sampling rate of 20 GSa/s and numerical bandwidth of 2 GHz. All PDIV measurements were performed in peak detect mode with frequency sampling fixed at 5 GS/s. PDIV values were measured 5 times for both materials under atmospheric pressure and at 20, 90, 110, 130, 150, 180 and 200 °C.

C. FEM Simulation

The potential and the electric field lines were computed for the same needle-plane configuration described previously thanks to COMSOL Multiphysics® (5.5). The implementation of the model using the AC/DC module of COMSOL (Electric current) in addition to the chosen meshing strategy in 2D axisymmetric format are described in a previous paper [8]. For instance, Fig. 2 presents the needle-plane model geometry in the case of PI material as well as the region of great interest where PDs firstly ignite.

FEM simulations were performed with a difference of electrical potential between the needle and the grounded electrode of 100 V<sub>peak</sub> was applied at 50 Hz and the materials properties are adjusted for different temperatures corresponding to experimental tests. Furthermore, the dielectric constant $\varepsilon'_e$ and the conductivity $\sigma_{AC}$ of PI and PTFE were defined for each temperature by interpolating values obtained from dielectric measurements as a function of the electric field and the frequency as discussed in [8]. Whereas $\varepsilon'_e$ and $\sigma_{AC}$ of air are considered unchanged with the modification of temperature (1 and 10<sup>-16</sup> S·m<sup>-1</sup> respectively) [9]. The computed distribution of the electric field lines and the scalar potential, as well as the applied voltage, will be integrated laterally in a specific numerical software named AIRLIFT, developed at IRT Saint Exupéry, to predict PDIV using Townsend's theory.

D. AIRLIFT and $\gamma$ Estimation

AIRLIFT is an in-house developed numerical software that has been used to predict PDIV in different systems. This software uses the electric field and electric potential calculated in COMSOL as inputs, and then estimates the PDIV for a given set of environmental parameters based on Paschen's law established from Townsend's theory where $\gamma$ is a parameter that can be modified. The approach presented in [8] showed that PDIV prediction with AIRLIFT is quite robust in this needle-plane configuration. In that case, a maximum deviation under 5% between the average experimental and computed PDIV was found for a polyimide sample using a value of $\gamma = 4.8\times10^{-4}$ found by P. Collin et al. [3]. An accurate estimation of $\gamma$ values for each material at different temperatures is key.

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**Fig. 1.** Experimental setup for PDIV measurements including needle-plane electrode system

**Fig. 2.** Needle-plane model
parameter for this approach and this assessment can be achieved as described in Fig. 3.

Once the electric field lines and the potential are computed by FEM at a specific temperature, PDIV is calculated in AIRLIFT for every electric field line where $\gamma$ was varied in the range of $10^{-6}$ to $10^{-2}$.

Fig. 3. Synoptic diagram of the proposed method for $\gamma$ estimation

Whereas, A and B coefficients of Paschen equation were set from literature as: $A=15$ (Torr.cm)$^{-1}$ and $B=365$ V.(Torr.cm)$^{-1}$ [5]. In fact, these two parameters depend mainly on the gas composition and are found to be constant over a range of a reduced electric field $E/p$ between 100 and 800 V. (Torr$^3$.cm$^{-1}$) [5], which is the case in this paper. Thereafter, the calculated PDIV values were fitted with a logarithmic function of $\gamma$ at each temperature. At this stage, $\gamma$ associated to every measured PDIV can be determined from the interpolated graphs $PDIV_{estimated}=f(\gamma)$.

III. RESULTS AND DISCUSSION

A. PDIV Measurements

Fig. 4 shows the evolution of measured PDIV ($V_{peak}$) versus temperature for PTFE and PI. As indicated by the error bars, the statistical dispersion on the experimental results is low; less than 4 % for PTFE and 6 % for PI.

Fig. 4. Measured PDIV for PI and sintered PTFE versus temperature

As far as PTFE is concerned, PDIV decreases by about 28 % from 20 to 200 °C. On the other hand, a slight decrease of PDIV of about 14 % was obtained in the case of PI.

In fact, the impact of the temperature is not the same for both materials since the electric field configuration is quite different due to the difference in material thicknesses as well as to their dielectric properties (for instance a dielectric constant of $\sim$2.5 for PTFE against $\sim$3.2 for PI at 50 Hz / 20 °C).

B. $\gamma$ Estimation with Temperature

The computed PDIV has been plotted versus $\gamma$ and the obtained results are illustrated in Fig. 5. At the first glance, PDIV has a quasi-linear upward trend with decreasing log($\gamma$) at all temperatures. Indeed, for each decade rise in the parameter $\gamma$, PDIV is reduced by about 150–170 $V_{peak}$ for PI and 180–230 $V_{peak}$ for PTFE. This provides a clue about the sensitivity of PDIV estimation to $\gamma$ coefficient in needle-plane systems. Moreover, $\gamma$ has been estimated for every measured PDIV as described above in II.D. Also, the variations of the calculated $\gamma$ with temperature for PI and PTFE are shown in Fig. 6. Each data point represents the average of 5 determined $\gamma$ values from every measurement and its associated error bars show the standard deviation. For instance, different results have been obtained at 20 °C, i.e.: $6.5\times10^{-4}$ and $10^{-5}$ for PI and PTFE respectively which are much lower than the traditional value found in the literature for metallic electrodes ($10^{-2}$). This result is not very surprising since the two materials have different physicochemical composition. In addition, the obtained results of PI by our methodology have the same order of magnitude as those reported in [3] and [6].
As far as polyimide is concerned, calculated $\gamma$ values seem to be slightly influenced by temperature. In contrast, it can be observed in Fig. 6 that the second ionization coefficient has some dependence on temperature in the case of sintered PTFE. However, it is noteworthy to mention that it is not yet understood whether this outcome could be related to the effect of thermo-ionic emission or to the changing of PTFE thickness with temperature, which is not considered in FEM calculations. The maximum decrease of PTFE thickness between 20 and 200 °C was estimated to be about 9 µm. To further clarify the contribution of $\gamma$, PDIV has been computed at various temperatures with $\gamma$ estimated at 20 °C and with $\gamma = 0.01$. The computed results are then compared with experimental ones as demonstrated in Fig. 7.

Although, the predicted PDIV with $\gamma = 0.01$ is more than 30% lower than the measured one for sintered PTFE.

**IV. Conclusions**

The main contribution of the authors includes the estimation of Townsend’s secondary ionization coefficient $\gamma$ for a “needle/dielectric film/plane” system in the presence of insulating polymers. It has been shown that using the estimated value of $\gamma$ found at 20 °C instead of the common value of 0.01 lead to significantly minimize the errors between simulations and measurements of PDIV. Therefore, high accuracy of PDIV prediction can be achieved at higher temperatures.

Our next objective would be expanding the study of PDIV prediction to more complex geometries, such as aeronautical cables, using our experimental simulation approach in addition to the results of this work. Since $\gamma$ depends on the electrical field distribution, it is expected to obtain higher $\gamma$ values when the needle electrode becomes thinner. It is also planned to investigate $\gamma$ for other insulating materials using the proposed approach.
REFERENCES


