Relationship between the Physicochemical Properties of Materials and the Fractal Dimension of Creeping Discharges Propagating at Solid/Fluid Interfaces

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***Abstract*— The present paper is aimed at the main parameters that affect the fractal dimension *D* of creeping discharges propagating over different types of insulators immersed in gases at different pressures or in dielectric liquids, in a point-plane electrode arrangement. Especially, the dielectric constant, thickness of insulators, gas pressure, type of liquids (mineral and vegetable oils) and the type of voltage waveforms (lightning impulse voltage or DC) are analyzed. The considered insulators are circular samples of different thicknesses made of different materials (namely, glass, epoxy resin, PTFE, phenolplast resin and pressboard). The fractal dimension *D* of the observed discharge patterns is determined by the box counting method. It is shown that *D* depends on the thickness (*e*) and the dielectric constant of insulator (ε), gas and its pressure or type of liquid. In a given gas or liquid, *D* decreases when *e* increases and it increases with ε; this dependency of *D* upon *e* and ε indicates the important role of the electric field and capacitive effect in the propagation mechanism. Also, *D* decreases when the gas pressure is increased; and *D* is higher with lightning impulse voltage than with DC voltage. However, in liquids, *D* decreases when increasing the dielectric constant of liquid. These results evidence the existence of a relation between the fractal dimension and the physicochemical parameters of both materials constituting the insulating mixed structure.**

Keywords*— *Creeping discharges, solid/gas interface, solid/liquid interface, stopping length, gas pressure, fractal analysis.

I. INTRODUCTION

The solid/fluid (gas or liquid) insulating systems are widely used in high voltage equipment. This includes oil filled apparatus as power transformers and capacitors, bushings, circuit breakers, cables ends and connectors; and components using gas (air, various gas and mixture, air) such as switchgears, gas insulated lines, circuit breakers, insulators … These mixed insulations systems are exposed to different stresses and particularly to discharges phenomena that can develop within the body of insulator or at the solid/gas interface leading respectively to breakdown or flashover of insulator and hence to the failure of the system. Thus the knowledge of the characteristic parameters of these discharges is of a great interest for the design and the dimensioning of insulation systems used in high voltage components and systems.

During the last two decades, intense researches have been achieved in our laboratory on the optical and electrical characterization of creeping discharges propagating at solid/liquid and solid/gas interfaces under AC, DC and lightning impulse voltages. These investigations concern especially the morphology (pattern) and stopping length of discharges and their evolution versus the dielectric constant and thickness of insulator material, the amplitude and polarity of voltage, type of gas (resp. mixture) and its pressure, type of liquids (mineral, synthetic and vegetable oils) and hydrostatic pressure applied to it [1-7].

It was reported that the shape of discharges and their stopping lengths L_f depend significantly on the solid insulator through its dielectric constant and thickness and the type of immersing medium (gas/mixture or liquid). For given solid or fluid, L_f increases quasi-linearly with the voltage and decreases when the gas pressure or hydrostatic pressure (in the case of liquid) increases [1-7]. The higher the pressure, the shorter the discharge channels are. For given voltage and pressure, L_f is longer when the point electrode is positive than when it is negative while the initiation voltage of discharges is higher with a negative point than with a positive one; and L_f is longer for higher dielectric constant of insulator. Also, when the thickness of insulator is reduced, the density and the length of branches increase indicating the implication of electric field and the capacitive effects. And for a given thickness of insulator, the density and the length of branches are reduced when the pressure (gas pressure or hydrostatic pressure in the case of solid/liquid interface) is increased.

This paper reports on the fractal dimensions of creeping discharges propagating radially (i.e., with a sharp electrode perpendicular to insulator, in a point-plane electrode arrangement) over different types of insulators immersed in gases and dielectric liquids and especially on the correlation existing between the fractal dimension and the physical characteristics of the constituents of interface. It is a synthesis of different results obtained by my group during the last twenty years.

II. EXPERIMENT

The diagram of the experimental setup consists of high voltage supply, a test cell containing a point-plane electrode arrangement and a CCD camera placed above the transparent cover of the test cell and connected through a video acquisition card (Meteor-II/Multi-Channel) to a computer (Figure 1). The test cell consists of a cylindrical core of 90 mm high and 110 mm inner diameter, and two flat circular covers. The upper cover was of PMMA (transparent material) enabling to visualize the discharge and to support the point electrode; the lower one which constitutes also the electrode plane, was of brass. The point electrode is made of tungsten, the radius of curvature r_p of which is 10 µm; it is placed perpendicularly to solid insulating sample. The voltage sources were either a Marx generator (200 kV - 2 kJ - 1.2/50 µs) providing a standard lightning impulse voltage or 200 kV DC generator. More details can be found in [1-7].

The solid insulating samples are discs of 100 mm diameter and thickness varying from 2 to 20 mm. These are made of different materials (glass, epoxy resin, polytetrafluoroethylene (PTFE), phenoplast resin (bakelite), pressboard), the dielectric constant ε of which varies between 2.1 to 5. The test cell is filled with gas (for instance, SF_6) at different pressures or insulating liquid (mineral, synthetic or vegetable oil).

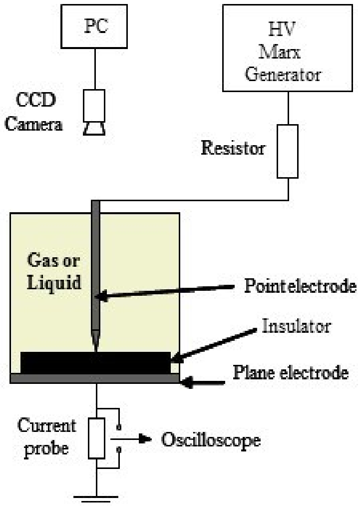

Figure 1. Experimental scheme of set-up

III. FRACTAL ANALYSIS TECHNIQUE

Figure 2 gives two examples of discharges at solid/gas and solid/liquid interfaces. To analyze and compare the fractal dimension *D* of creeping discharges developed over different solid/gas and solid/liquid interfaces, and the influence of parameters that can influence *D*, one considers discharges of the same stopping length S. For this, we proceed as follows: for given type of insulator, insulator thickness, gas/liquid and pressure, the voltage is increased up to reach the chosen S. And depending on the investigated parameter, one varies one of these parameters.

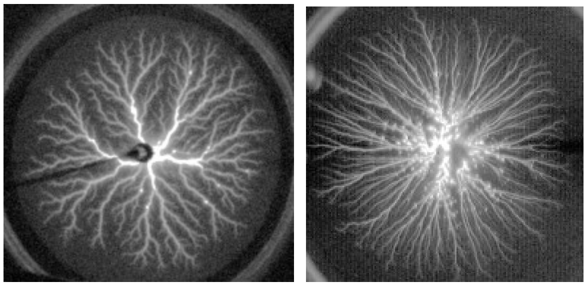
(a) (b)

Figure 2. Examples of creeping discharges propagating: (a) over PTFE sample of 2 mm thickness in presence of SF6 at 0.3 MPa, under positive lightning impulse voltage of crest value of 17 kV; and (b) over discharges over phenoplast resin (bakelite) sample in mineral oil at ambient under negative lightning impulse voltage of a crest value of 40 kV.

IV. COMPUTATION OF FRACTAL DIMENSION

There are many methods to estimate the fractal dimension *D* of a self-similar structure [8-11]. However as we showed in previous work, the most adapted method for surface discharges is the box counting method [1]. This method consists in converting the original figures of discharges into binary figures that are then processed with software we developed in our Lab [1] (Figure 3).

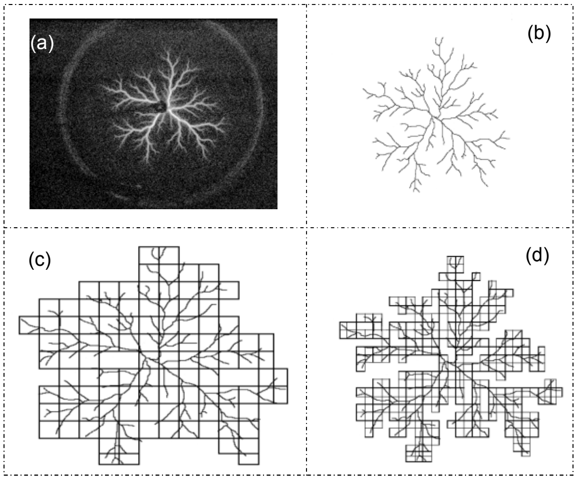

Figure 3. Different steps of box counting processing: (a) original figure, (b) the corresponding binary figure, (c) and (d) the binary figure covered by squares of side *l*= 45 pixels and *l*= 15 pixels, respectively. The treated figure is that of surface discharge propagating on PTFE insulator of 2 mm thickness in SF6.

The principle of this software consists in generating square boxes of slide *l* the magnitude of which are changed at each step up to cover totally the considered figure. The total number of boxes *N(l)* containing any branch of discharge for each value of *l* enables to determine the fractal dimension *D* according to equation

$$N(l) \sim l^{-D} \qquad (1)$$

Indeed, by plotting N versus l in log-log representation, one deduces D which is the slope of linear part of this characteristic knowing that

$$D = -\lim_{l \to 0} \frac{\log N(l)}{\log l} \qquad (2)$$

Figure 4 shows examples of the evolution of the total number of boxes N versus the side length l of boxes for discharges propagating over epoxy resin samples of different thicknesses in SF_6 at 0.10 MPa. And Figure 5 depicts an example of $N(l)$ for surface discharges on pressboard in mineral oil for different thicknesses.

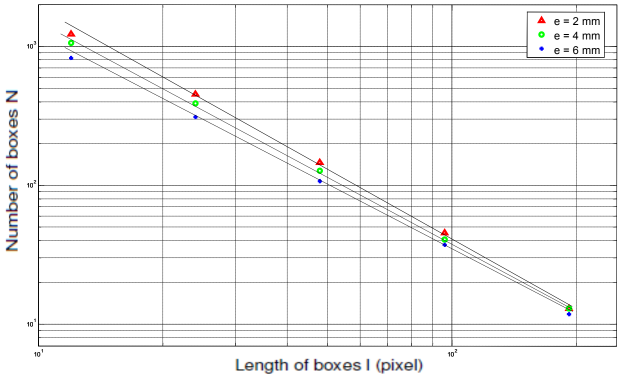

Figure 4. Total number of boxes N *vs*. the side length l of boxes for discharges propagating over phenoplast resin samples of different thicknesses in SF_6 at 0.1 MPa under positive lightning impulse voltage; D ≈ 1.64, 1.58, 1.53 respectively for (e = 2 mm, +31 kV), (e = 4 mm, +33,6 kV) and (e = 6 mm, +36 kV).

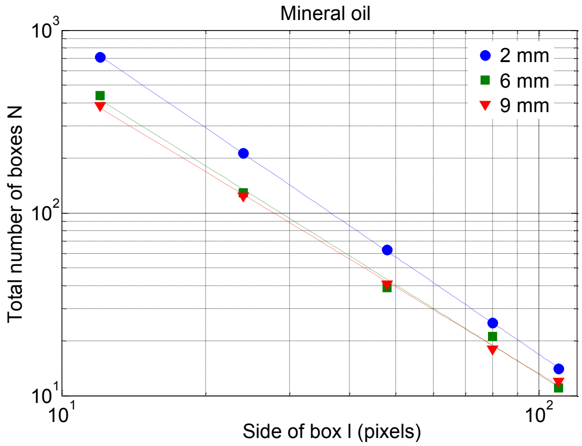

Figure 5. Total number of boxes N versus the side length l of the boxes obtained from the analysis of examples of discharges propagating of pressboard immersed in mineral oil, using the box counting method: $D \approx 1.77$, 1.63 and 1.58, respectively for 2, 6 and 9 mm pressboard thicknesses.

V. COMPUTATION OF FRACTAL DIMENSION

A. Fractal Dimension of Discharges at Solid/Gas interface

From the $N(l)$ characteristics, one can deduce the fractal dimension D for different parameters. Tables 1 and 2 give D for different thicknesses of a given insulator material at a given gas pressure or for different gas pressures for a given insulator under lightning impulse voltage. And Tables 3 and 4 give D for the same parameters under DC voltage.

We observe that D decreases when the insulator thickness increases. And for a given insulator thickness, D increases with the dielectric constant of insulator.

TABLE 1: Influence of thickness and type of insulation samples on the fractal dimension D of discharges propagating at solid/SF6 interface at P = 0.10 MPa, under positive lightning impulse voltage.

Thickness of insulation samples e (mm)	*Fractal dimension D*		
	PTFE $\varepsilon = 2.1$	Epoxy resin $\varepsilon = 3.4$	Glass $\varepsilon = 5.0$
2	1.51 ± 0.02	1.64 ± 0.02	1.77 ± 0.02
4	1.45 ± 0.02	1.58 ± 0.02	1.70 ± 0.02
6	1.41 ± 0.02	1.53 ± 0.02	1.65 ± 0.02

TABLE 2: Fractal dimension of discharges on different insulators in SF_6 of 2 mm thickness at different gas pressure under positive lightning impulse voltage.

Gas pressure P (MPa)	*Fractal dimension D*		
	PTFE $\varepsilon= 2.1$	Epoxy resin $\varepsilon= 3.4$	Glass $\varepsilon= 5.0$
0.15	1.53	1.62	1.78
0.30	1.52	1.58	1.58
0.50	1.40	1.52	1.66

TABLE 3: Influence of thickness and type of insulator samples on the fractal dimension D of discharges propagating at solid/SF6 interface at P = 0.30 MPa under positive DC voltage.

	Dielectric Constant ε	Thickness *of insulator e* (mm)		
		2	5	9
Phenoplast resin	4.8	1.50	1.47	1.43
Glass	5.0	1.58	1.54	1.47

TABLE 4: Fractal dimension of discharges on different insulators of 2 mm thickness in SF_6 at different gas pressure under positive DC voltage.

	Dielectric Constant ε	Pressure P (MPa)		
		0.1	0.2	0.3
Phenoplast resin	4.8	1.56	1.53	1.44
Glass	5.0	1.58	1.54	1.47

Thus, the ramification degree of discharges is well correlated with the characteristics of insulator (dielectric constant ε and thickness e). The fact that the density of discharge branches expressed by the fractal dimension depends on the thickness and the type of insulator (dielectric constant) evidences the implication of capacitive effects on the propagation phenomena of creeping discharges.

B. Fractal Dimension of Discharges at Solid/Liquid interface

Similarly as for discharges at solid/gas interface, from the $N(l)$ characteristics, one can deduce the fractal dimension D for different parameters. Table 5 gives D for different thicknesses *e* of a given insulator material under lightning impulse voltage. Table 6 gives *D* for different thicknesses of pressboard in mineral and vegetable oils, under positive lightning impulse voltage.

One observes that *D* decreases when the insulator thickness increases. And for a given insulator thickness, *D* increases with the dielectric constant of insulator.
However, when the dielectric constant of oil increases, *D* decreases.

TABLE 5: Influence of thickness and type of insulation samples (*e*) on the fractal dimension *D* at atmospheric pressure under positive lightning voltage. Dielectric constant of mineral oil $\varepsilon = 2.2$.

	Dielectric Constant ε	Thickness of insulator *e* (mm)		
		2	10	20
Polycarbonate	2.9	1.63±0.02	1.58±0.02	1.52±0.02
Phenoplast resin	4.8	1.73±0.02	1.65±0.02	1.57±0.02
Glass	5.0	1.75±0.02	1.66±0.02	1.60±0.02

TABLE 6: Influence of thickness of pressboard samples (*e*) and type of oil on the fractal dimension *D* at atmospheric pressure under positive lightning voltage. Dielectric constant of pressboard $\varepsilon = 4.3$.

	Dielectric Constant ε	Thickness of insulator *e* (mm)		
		2	6	9
Mineral oil	2.2	1.77±0.02	1.63±0.02	1.58±0.02
Vegetable oil	3.2	1.72±0.02	1.62±0.02	1.59±0.02

VI. CONCLUSION

This work evidences the existence of a correlation between the fractal dimension *D* of creeping discharges propagating over insulators made of different materials immersed in gas or liquid, and the physical parameters of materials constituting the interface. It is especially showed that *D* decreases when the thickness (*e*) of insulator increases and/or the gas pressure *P* is increased; and it increases with the dielectric constant of insulator (ε). However, one notes that in presence of liquid (insulating oil), *D* seems to decrease when the dielectric constant of oil increases: *D* is higher with mineral oil $\varepsilon = 2.2$) than in vegetable oil ($\varepsilon = 3.2$). These results are of a great interest for the dimensioning of solid/gas and solid/liquid insulating systems in high voltage apparatus.

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