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ABSTRACT

This paper deals with the experimental characterization of discharges propagating over insulators of epoxy and glass, immersed in a gas or a gaseous mixture, under lightning impulse voltages (1.2/50 µs), using a point-plane electrode arrangement. The gases and mixtures we considered are SF_6, N_2, CO_2, SF_6-N_2 and SF_6-CO_2. The morphology of creeping discharges and their final lengths are investigated versus the kind of insulator material, the amplitude and polarity of the voltage, the type of the gas (resp. mixture) and its pressure. It's shown that the shape of discharges and their final (stopping) lengths L_f depend significantly on the solid insulator and the type of gas. For given solid and gas, L_f increases quasi-linearly with the voltage and decreases when the gas pressure increases. The discharges don't always present a radial structure as reported in literature. For given voltage and pressure, L_f is longer when the point electrode is positive than when it's negative while the initiation voltage of discharges is higher with a negative point than with a positive one; and L_f is longer with glass than with epoxy. L_f is shorter in SF_6 than in CO_2 or N_2. On the other hand, the increase of SF_6 content in SF_6-CO_2 mixture leads to a significant decrease of L_f. Therefore the addition of small concentration of SF_6 in a given gas mixture improve the dielectric strength of insulating structure.

Keywords - creeping discharges, final length, epoxy resin, glass, flashover

I. INTRODUCTION

The solid/gas insulating systems are widely used in high voltage engineering. The dielectric strength of such structures depends on the applied voltage, the properties of solid insulator, the kind of gas as well as the gas pressure and temperature. The behaviour of these insulating structures facing the different stresses and more especially the discharges which can develop within the body of each component (solid or gas) or at the solid/gas interface constitutes one of the main criteria of choice of a given insulating system.

The discharges propagating at gas/solid insulators have been the subject of numerous studies [1 - 3]. However the processes evolved in their development are not yet well understood. Several mechanisms have been proposed to explain the mechanisms implicated in the initiation and propagation of these kinds of discharges. Among these mechanisms, one can cite the dynamic interaction between the discharge and the insulator surface [4 - 6], the accumulation of electrical charge at the insulator surface [7 - 13], the modification of the ionization and attachment coefficient [14, 15] and the distortion of electric field [16, 17]. Therefore, the understanding of the initiation conditions of these creeping discharges and the parameters characterizing their development up to flashover is of great interest for the design and the dimensioning of high voltage components and systems (bushings, insulators, switchgears, gas insulating lines, gas circuit breaker …).

This paper is aimed at the experimental investigation of creeping discharges propagating over solid insulator issued from epoxy and glass, immersed in a gas or a gas mixture, under lightning impulse voltages (12/50 µs), using a point-plane electrode arrangement. We especially investigate the morphology of discharges and their final lengths versus the amplitude of the voltage, the type of solid material, the type of gas or gas mixture and pressure.

II. EXPERIMENT

The diagram of the experimental setup is given in Figure 1. The test cell containing the considered solid/gas insulating system (gas/solid) and a point-plane electrode arrangement consists of a cylindrical core of 90 mm high and 110 mm inner diameter, and two flats and circular covers; the upper cover was of transparent material polymethyl metachrilate (PMMA) enabling to visualize the discharges and to support the sharp electrode; the lower one which constitutes also the electrode plane is a circular plate of 250 mm diameter and 15 mm thickness, was of brass. The electrode point was made of tungsten with a radius curvature of 10 µm.

The solid insulating samples we inserted between the electrodes are discs of 100 mm diameter and 2 mm thickness. These are made of epoxy resin ($\varepsilon_r = 3.5$ and dielectric strength E_d = 22 kV/mm) and glass ($\varepsilon_r = 5$ and dielectric strength E_d = 10 kV/mm). Three gases (N_2, SF_6, CO_2) and mixtures of these gases (SF_6-N_2 and SF_6-CO_2) are investigated. The solid samples are changed each time we observe irreversible traces on the solid surface that can create preferential ways for the following discharges. A system of taps associated to two manometers enables to fill the test cell and to control the gas pressure. The tests are achieved under lightning impulse voltage (1.2/50 µs) supplied by a 200 kV Marx generator.

The optical observation of the discharges is based on the integrated images taken with the help of a CCD camera connected to a high performance video card. The CCD camera is a "SONY XC-HR58" type, high SVGA resolution (767x580 pixels) image capturing at a speed of 50 full frames/sec. It is set to record 900 images before stopping. During the image grab, the impulse voltage is applied. And thanks to the CCD camera and the video card (Meteor-II/Multi-Channel) to which it's connected, we get the image of the discharge in its maximum extension we called the final length of discharge, L_f.

III. Experimental results

The initiation threshold voltage U_0 of creeping discharges, their morphology and final lengths L_f mainly depend on the constituents of interface, i.e., the nature of insulator, the amplitude and polarity of the applied voltage, the kind of gas (mixture) and its pressure as well as the concentration of the different constituents of mixtures.

III.1 Initiation threshold voltage of creeping discharges

We observe that for given interface and gas pressure, the initiation threshold voltage U_0 are higher when the point is negative than when it's positive. Figure 2 gives an example with glass / SF6 interface. On the other hand, U_0 is generally higher in SF_6 than in CO_2 and N_2. In these two later gases, the values of U_0 are too close; it's also the case with SF_6-CO_2 and SF_6-N_2 mixtures. U_0 is also influenced by the type of the solid insulator material. Indeed, for given gas and pressure, U_0 is higher with epoxy than with glass whatever the polarity of point. This is due to the enhancement of electric field at the point electrode which is all the higher as the difference of dielectric constants between gas and insulator is important (the dielectric constant of glass being higher than that of epoxy).

III.2 Morphology of discharges

When the applied voltage is higher than U_0, the discharges (streamers) propagate over the insulator surface by steps as observed by Shibutani *et al* [18], describing a circular contour around the point electrode. For given interface and gas pressure, the final lengths of discharges are longer with a positive point than with a negative point. Figure 3 gives an example with glass / SF_6 interface at 0.2 MPa. On the other hand, the shape of discharges is not necessarily radial as reported by numerous researchers (Figure 4); it's clearly different from one polarity to another. The increase of pressure reduces the length of the discharges whatever the interface and polarity of the point electrode (Figures 5 to 7).

The addition of small concentration of SF_6 (electronic scavenger additive) to CO_2 reduces L_f. Figure 8 shows the influence of SF_6 concentration in CO_2 on the final length L_f. The higher the concentration of SF_6, the shorter L_f is whatever the polarity of voltage.

III.3 Final length of discharges

The final lengths of creeping discharges L_f is also influenced by the type of solid insulator and the gas as well as the gas pressure. L_f increases quasi-linearly with the voltage and decreases when the gas (resp. mixture) pressure is increased (Figures 9 to 15). However, this quasi-linearity is not well attended with glass when the point is positive (Figures 13 and 14). This can be due to the fact that: (*i*) when the discharges propagate over the surface of glass, they leave traces (furrows) that influence the discharge trajectories and then the final lengths [20]; and (*ii*) the space charge that can modify the electric field and then the propagation of discharges. Note that each point in these figures represents a mean value on at less six measurements. L_f is longer with CO_2 and N_2 than with SF_6. Consequently the flashover voltages are lower in CO_2 and N_2 than in SF_6 confirming thus the known dielectric properties (dielectric strength) of this latter with regards to CO_2 and N_2.

Note that in nitrogen, we observed important scattering of results and especially when the point is positive. Such observations have been already done on the measurements of the dielectric strength of N_2 under impulse voltages [23]. At relatively high pressures, the discharges observed in N_2 when the point is negative are similar to those obtained in SF_6 and CO_2.

The increase of concentration of SF_6 in SF_6-CO_2 or SF_6-N_2 mixtures leads to a decrease of the final length (Figures 12 and 15). However the effect is not very clear with 10% and 15% of SF_6 in SF_6-CO_2 mixture. This can be due to the existence of an optimum concentration of SF_6 over which the effect of pressure is not visible. As in pure nitrogen, we also observed an important scattering in the values of L_f in presence of SF_6-N_2 mixture for different concentrations of SF_6. Therefore the use of N_2 or N_2-SF_6 mixture could present risks for high voltage applications (circuit breakers for instance).

On the other hand, for given gas (mixture) and pressure, L_f is longer with glass than with epoxy whatever the polarity of point. This is due to the enhancement of both components (normal and tangential) of electric field which are all the higher as the difference of dielectric constants between gas and insulator is important. Thus, these components especially the tangential one being higher with glass than with epoxy, L_f will be longer with glass than with epoxy.

IV DISCUSSION

The fact that the positive discharges are longer than the negative ones is due to the physical mechanisms involved in each polarity. When the point is positive, the space charge reduces the field in the vicinity of point but enhances it in the direction of the opposite electrode facilitating the streamers propagation. Thus the streamers can develop at lower voltages than the negative ones. In the case of negative polarity, the space charge reinforces the electric field at the point but reduces it in the direction of the opposite electrode. The streamers slow down and the voltage required to their development will be higher.

On the other hand, for a given pressure and voltage

$$L_f\,(SF_6) < L_f\,(CO_2) < L_f\,(N_2)$$

whatever the polarity. This is due to the dielectric properties of SF_6. This latter acts by reducing the ionization phenomena and then the space charges which constitute a major factor influencing the electric field at the head of discharge channels. And the higher the gas pressure the weaker the charge carriers are and the shorter the discharge channels are.

By extrapolating the L_f (U) curves (straight lines) at L_f =0, one can deduce the threshold voltage U_0 of creeping discharges at a given solid/gas (mixture) interface and pressure. And as observed on the light emitted by discharges, U_0 is higher with negative point than with the positive point. Thus, for a given pressure, the $Lf(U)$ characteristics can be described by the following relationship

$$L_f(U) = k_v(U - U_0) \qquad (1)$$

k_v is a constant depending on both materials constituting the insulation system (solid and gas (type and pressure)). The threshold voltage U_0 over which a discharge is initiated varies with the pressure and the solid/gas system. It is all the higher as the pressure is high. Tables 1 and 2 summarize the values of initiation threshold voltage U_0 and slope k_v for SF6/epoxy + moulding layer and SF6/glass interfaces, and CO2/epoxy + moulding layer and CO2/glass interfaces respectively versus gas pressure and the polarity of point electrode. Note that k_v is higher with a positive point than with a negative one; and it's higher with glass than with epoxy.

The fact that the pressure acts on the discharge reducing their volume, the length and density of their branches indicates the influence of gaseous nature of discharges. The creeping discharges propagating over epoxy with moulding layer present a maximal extension (L_f) relatively higher than that measured with polytetrafluoroethylene filled with mineral fillers in the same experimental conditions [19]. It appears that, for a given voltage, there is a pressure for which any discharge can appear as we reported for solid/liquid interface [20 - 22]. Therefore the increase of gas pressure enables to improve the dielectric strength of a given solid/gas (mixture) insulating system.

V. CONCLUSION

This study shows that the discharges pattern and final length, L_f, of creeping discharges depend on the amplitude and polarity of the voltage, the kind and pressure of gas, the constituents of gas mixture and the solid sample. The initiation threshold voltage U_0 is higher with a negative point than with a positive one; and it's higher with epoxy than with glass. For given gas (mixture) and pressure, L_f is longer with glass than with epoxy whatever the polarity of point.

For a given gas or mixture, the final length of discharges L_f generally increases quasi-linearly with the voltage; it's reduced when the pressure is increased.

L_f is shorter in SF_6 than in CO_2 or N_2. And the addition of small content of electronegative gas reduces L_f and thence improves the dielectric strength of the insulating structure. L_f is higher with a positive point electrode than with a negative one indicating thus that the penalising polarity is the positive one. This is of a great interest for the dimensioning of electrical apparatus with gaseous insulation. In N_2, the values of L_f present a significant scattering from one shoot to another. This constitutes a risk if one has to use N_2 or SF_6-N_2 mixture in high voltage apparatus.

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Table 1: Values of initiation threshold voltage U_0 and slope k_v for SF6/epoxy + moulding layer and SF6/glass interfaces versus gas pressure and polarity of point electrode.

Gas pressure (MPa)	0.05		0.1		0.15		0.2	
Voltage polarity	+	-	+	-	+	-	+	-
Interface	**SF6/Epoxy+moulding layer**							
U_0(kV)	25.5	25.9	26.7	30.7	30.0	33.7	30.8	36.0
k_v (mm/kV)	3.6	1.17	2.6	1.17	3	1.16	3	1.15
Interface	**SF6/Glass**							
U_0(kV)	18.0	19.5	20.4	21.3	23	23.6	24	28.0
k_v (mm/kV)	6.8	3.8	7.0	3.8	7.0	3.8	7.0	3.8

Table 2: Values of initiation threshold voltage U_0 and slope k_v for CO2/epoxy + moulding layer and CO2/glass interfaces versus gas pressure and polarity of point electrode.

Gas pressure (MPa)	0.1		0.2		0.3		0.4		0.5	
Voltage polarity	+	-	+	-	+	-	+	-	+	-
Interface	**CO2/Epoxy+moulding layer**									
U_0(kV)	19.0	33	22.3	34	23.5	38	24.5	41	27.0	42
k_v (mm/kV)	4	2.1	3	1.9	3	1.8	2.9	1.8	2.9	1.8
Interface	**CO2/Glass**									
U_0(kV)	16.0	22.6	16.7	26	17.0	28	18.6	29.0	19.3	31.5
k_v (mm/kV)	8.3	5	7	5	5.3	4	6.7	4.1	6.7	3.2

Figures

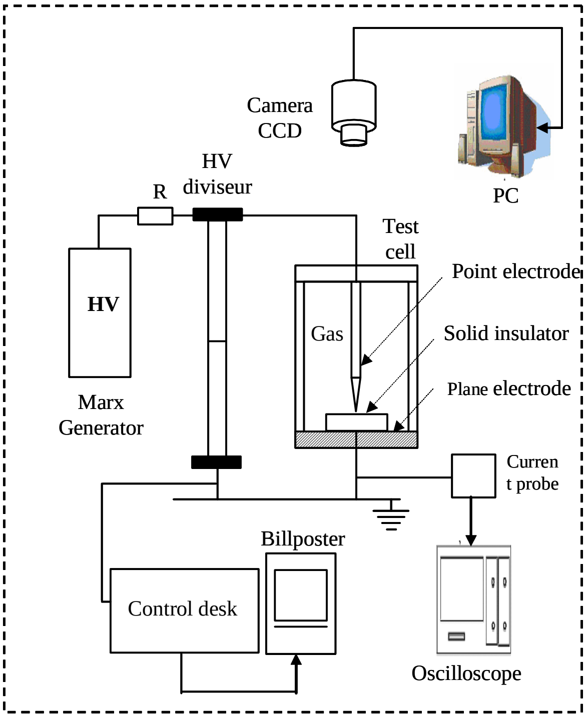


Figure 1. Scheme of experimental setup

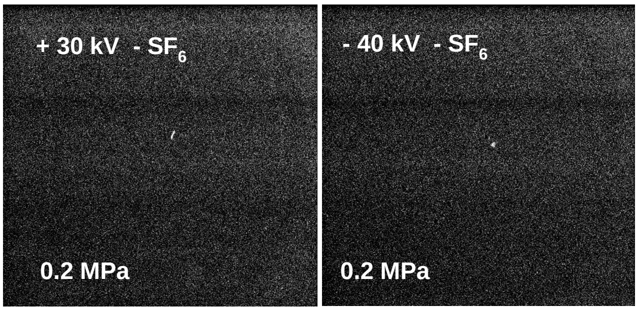


Figure 2. Comparison of the positive and negative initiation threshold voltages of creeping discharges for epoxy resin / SF_6 interface at 0.2MPa

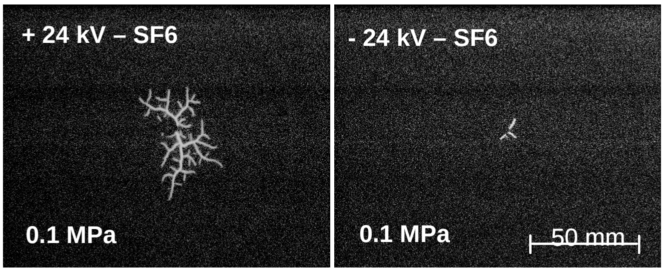


Figure 3. Influence of the polarity of voltage and gas pressure on the final length of discharges propagating over glass/SF_6 interface

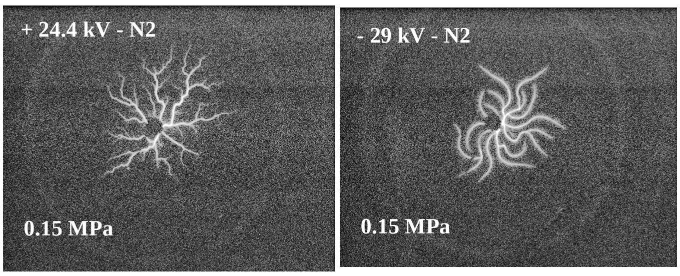


Figure 4. Morphology of positive and negative discharges propagating over glass / N_2 interface at a pressure of 0.15 MPa

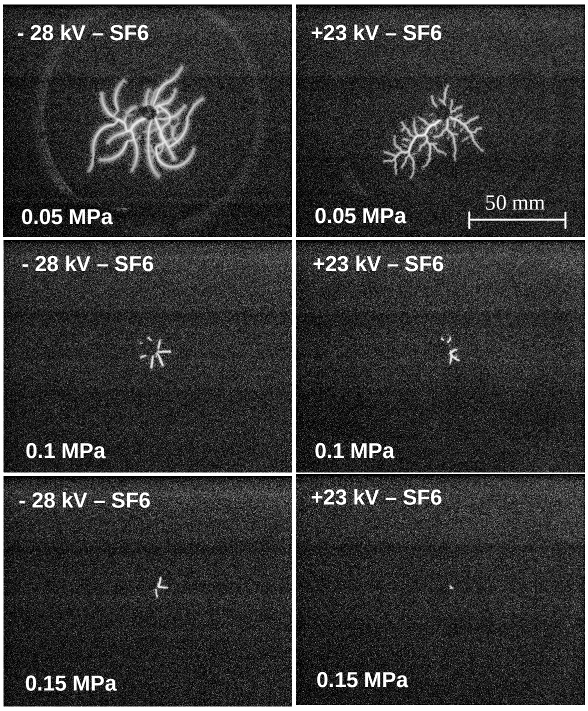


Figure 5. Influence of gas pressure and polarity of voltage on the final length of discharges propagating over a glass/SF_6 interface

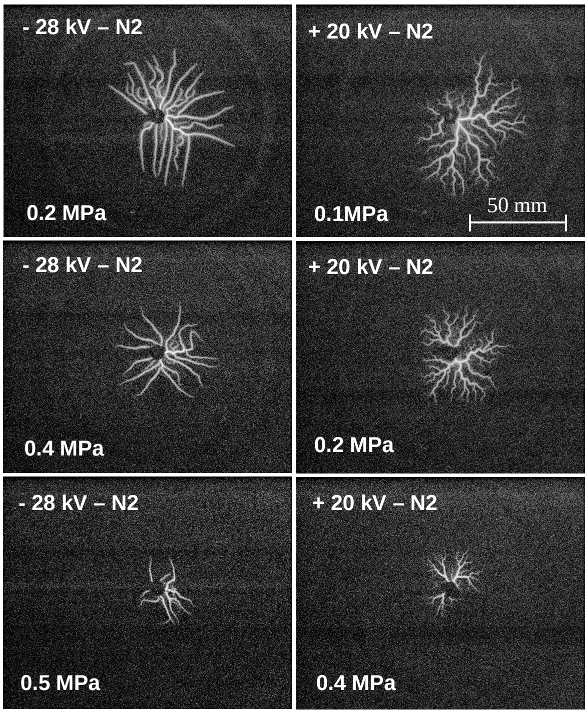


Figure 6. Influence of gas pressure and polarity of voltage on the final length of discharges propagating over a glass/N_2 interface

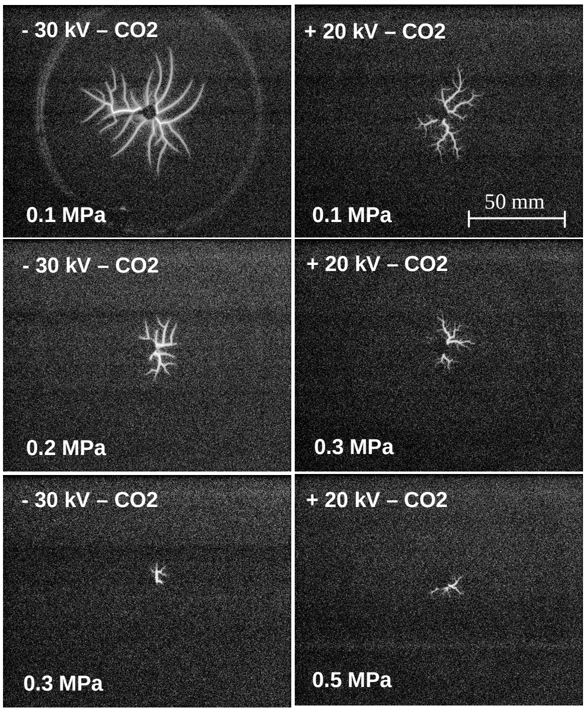
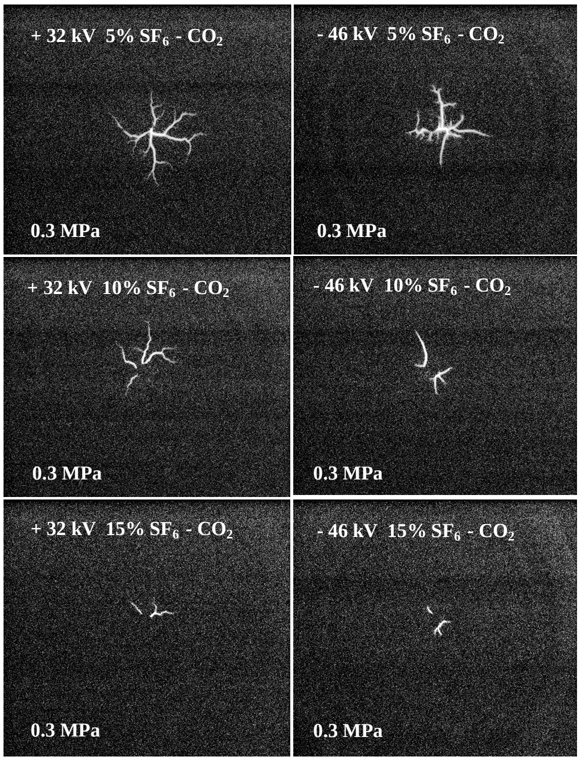
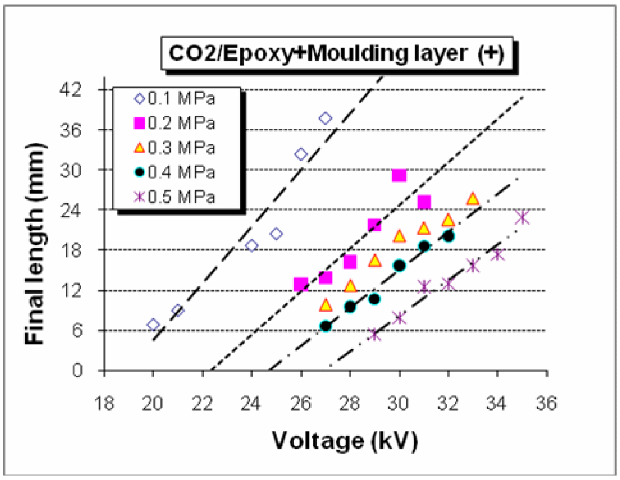


Figure 7. Influence of gas pressure and polarity of voltage on the final length of discharges propagating over a glass/CO_2 interface

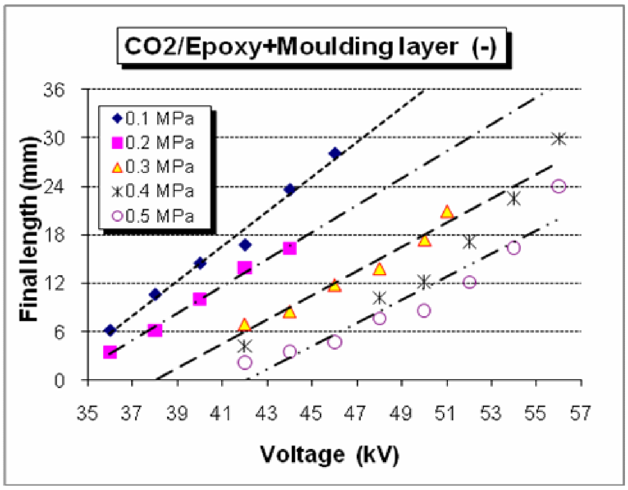


(a) **(b)**

Figure 8. Influence of SF_6 content in CO_2 at 0.3MPa on creeping discharges propagating over epoxy resin for both polarities: (a) positive and (b) negative

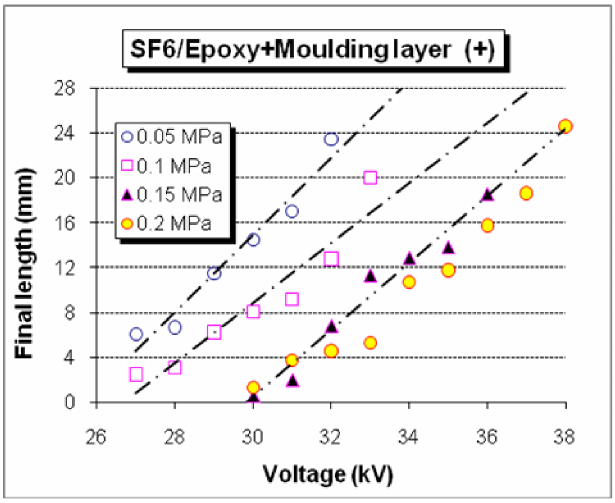


(a)



(b)

Figure 9. Final length of creeping discharges over epoxy resin immersed in CO_2 versus the voltage for positive and negative point and for different pressures



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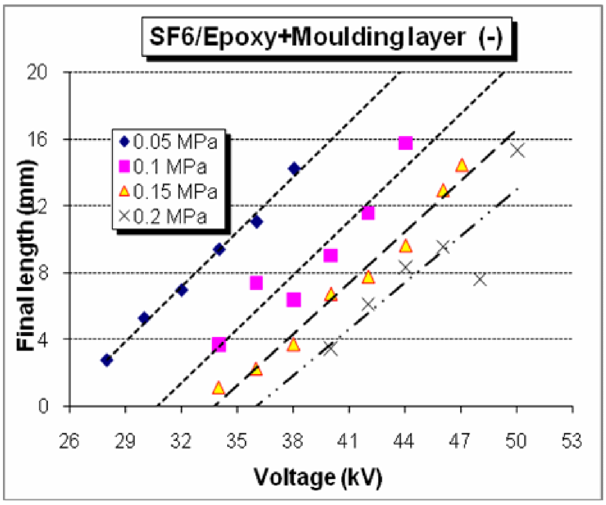
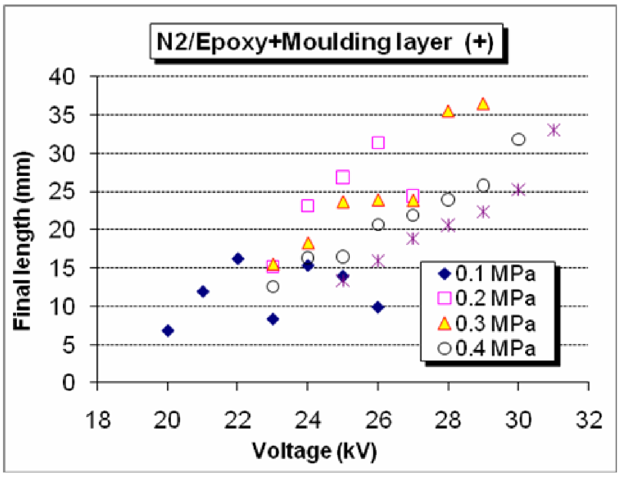


(b)

Figure 10. Final length of creeping discharges over epoxy resin immersed in SF_6 versus the voltage for positive and negative point and for different pressures



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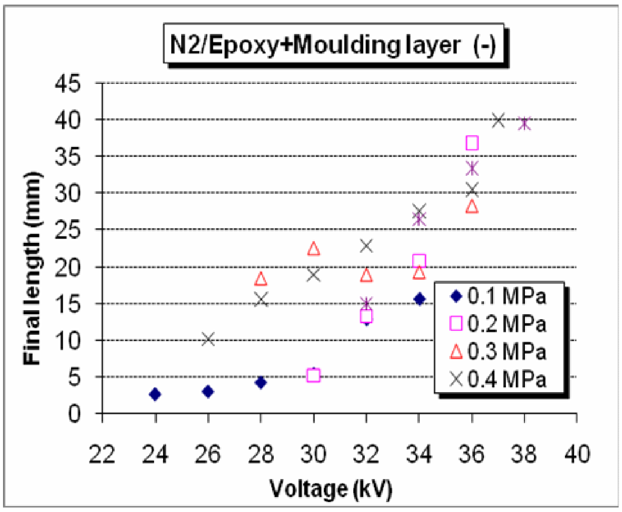
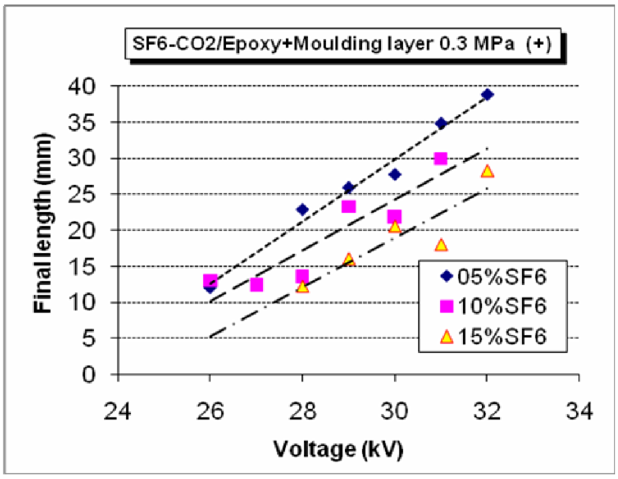
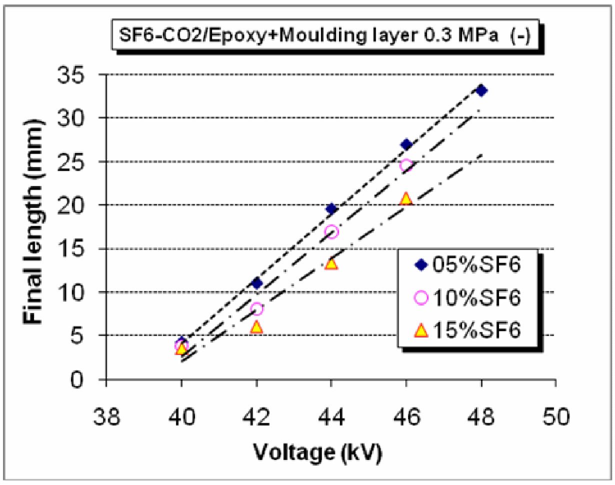


(b)

Figure 11. Final length of creeping discharges over epoxy resin immersed in N2 versus the voltage for positive and negative point and for different pressures.



(a)



(b)

Figure 12. Final length of creeping discharges over epoxy resin immersed in CO2-SF6 mixtures at 0.3MPa versus the voltage for positive and negative point and for different pressures: (a) positive polarity, (b) negative polarity

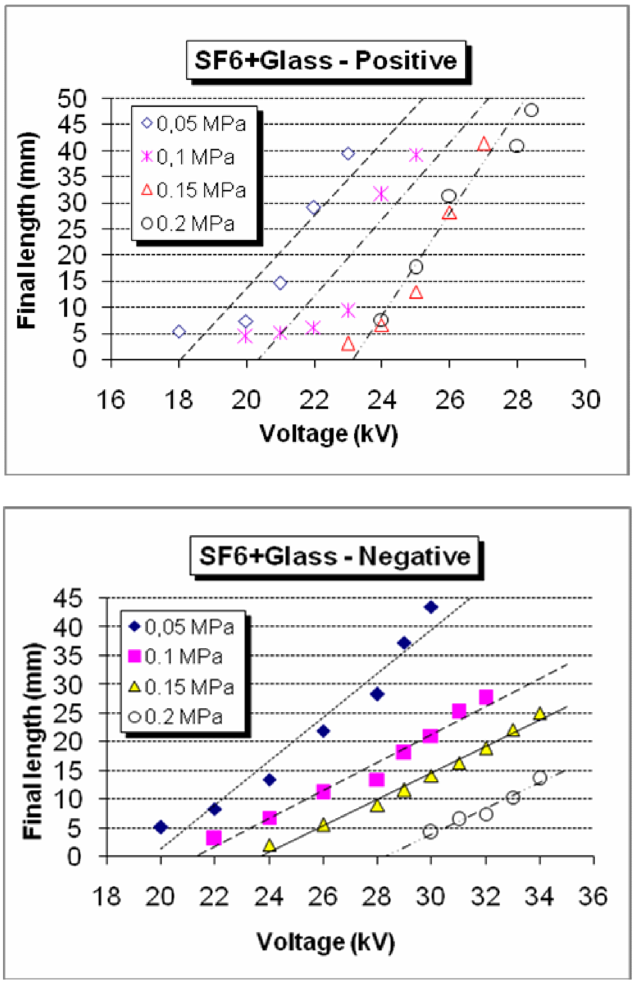


Figure 13. Evolution of the final length versus the voltage in SF_6 for both polarities and for different pressures

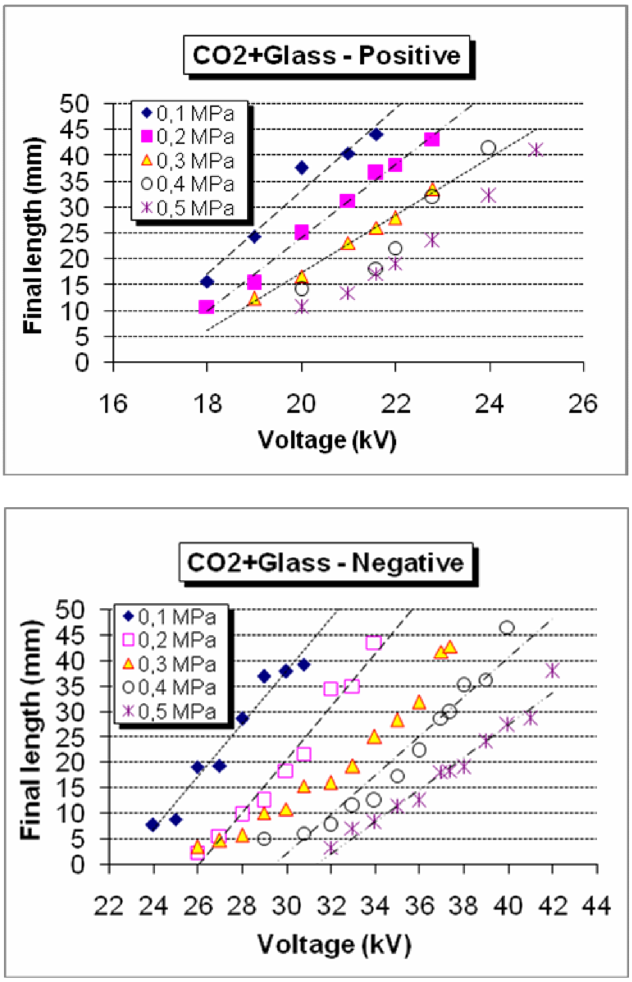
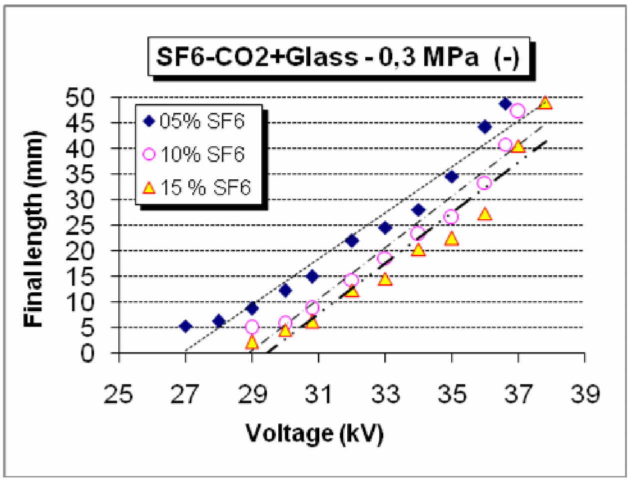


Figure 14. Evolution of the final length versus the voltage in CO_2 for both polarities and for different pressures



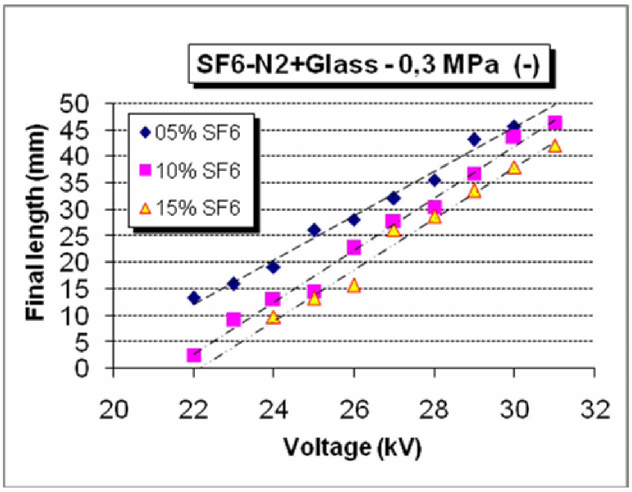


Figure 15. Evolution of the final length versus the voltage in SF_6-CO_2 and SF_6-N_2 mixtures for a negative point and for different pressures