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# Measurement of Streamer Propagation Velocity over Solid Insulator Surface in a $C_4F_7N/CO_2/O_2$ Mixture under Lightning Impulse Voltages

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## ABSTRACT

For a better understanding of the discharge development over a solid insulator surface, experiments are conducted over epoxy-anhydride resin samples in a  $C_4F_7N/CO_2/O_2$  mixture under lightning impulse voltages. A measurement method of streamer propagation velocity using a photomultiplier is presented. It is observed that the propagation velocity greatly depends on the gas nature, the polarity of the voltage, and the high voltage electrode geometry. The involved mechanisms in propagation are also discussed.

Index Terms — fluoronitrile,  $C_4F_7N/CO_2/O_2$  mixture, epoxy-anhydride resin, surface discharge, streamer velocity.

## 1 INTRODUCTION

SULFUR hexafluoride ( $SF_6$ ) is currently the most used gas in high voltage equipment such as Gas Insulated Substations (GIS), because of its excellent dielectric properties. Yet, because of its high global warming potential (GWP), it is one of the gas targeted by the Kyoto protocol, aiming to reduce or ban their use. Thus, manufacturers and investigators are looking for more eco-friendly alternative gas/mixtures. One of the solution suggested includes a compound from the fluoronitrile family, the heptafluoro-isobutyronitrile ( $C_4F_7N$ ), presenting a low GWP and a dielectric strength almost twice that of  $SF_6$  at equal pressure [1]. However, because of its boiling point of  $-4.7^\circ C$ , it must be mixed with a buffer gas for low temperature applications [1–3]. Carbon dioxide ( $CO_2$ ) was chosen for this purpose. With the proper pressure and  $C_4F_7N$  ratio, the resulting mixture presents insulating performances close to  $SF_6$ , as well as a significant reduction in GWP [1]. Several studies have been conducted on the  $C_4F_7N/CO_2$  mixture, to explore its dielectric strength [2–4], decomposition products and physicochemical behavior [5].

In addition to its insulation property, the  $C_4F_7N/CO_2$  mixture is also destined to replace  $SF_6$  for arc quenching applications. To facilitate gas handling by limiting the number of mixtures to use, manufacturers are looking for a unique one usable for insulation and circuit breakers. When an electric arc occurs in gas, solid carbon can appear [6] and be deposited over solid insulators surface, reducing thence the dielectric strength. It has been theoretically [6] and experimentally [7] demonstrated that the

addition of di-oxygen ( $O_2$ ) can reduce the carbon decomposition products, thus encouraging the manufacturers to add  $O_2$  in the mixture. Besides, it was observed that for a fixed  $C_4F_7N$  ratio and a  $O_2$  ratio varying from 0 to 10%, its addition does not have influence on the effective ionization rate coefficient of the mixture [8].

Apart from the gas alone, another essential item for GIS design is the solid spacer supporting the conductor. Thus, it is fundamental to understand the electric discharge development at the gas/solid interface. The triple junction between conductive part, solid spacer and gas/mixture (also called triple point) constitutes a weak point for electrical insulation, where the creeping discharges can be initiated. Discharge development at the gas/solid interface was studied by many researchers with  $SF_6$  and  $SF_6$  gas mixtures [9, 10]. A study with a  $C_4F_7N/CO_2$  mixture and samples of epoxy resin was previously carried out using radial geometry [11]. Most of the results reported in literature about the mixture/solid interface deal with the flashover voltages [12]. The question of surface charges with these mixtures is also addressed [13, 14]. Thus, the surface withstand of mixture containing 5% of  $C_4F_7N$  over epoxy resin is estimated around 70% of those of  $SF_6$  at the same pressure, requiring to use the mixture at higher pressure than  $SF_6$  to obtain equivalent performance.

B. Zhang *et al* [13], by the surface charge measurement of spacers in  $C_4F_7N/CO_2$  mixtures under DC voltage, reveal that the surface charge density decreases slightly with the increase of  $C_4F_7N$  content. However, the surface charging level in 25%  $C_4F_7N$  mixture is still much higher than that in  $SF_6$  and most of the surface charge stems from partial discharges (PDs) near the flange. There are more PDs with low magnitude, but much less PDs with high magnitude compared to that in the 15~25%  $C_4F_7N/CO_2$  mixtures.

It is the different PD behaviors between  $C_4F_7N/CO_2$  mixtures and  $SF_6$  that lead to their different surface charging characteristics.

The present paper is aimed at the development of the discharge leading to flashover at the solid insulator –  $C_4F_7N/CO_2/O_2$  mixture interface, under a tangential electric field geometry. The study of the streamers/discharges propagation can help to understand the mechanisms of trapping/de-trapping and ionization of charge carriers in new gas mixture that is  $C_4F_7N/CO_2/O_2$  mixture and hence to better understand the dielectric properties of these mixtures and support its use as an alternative solution to  $SF_6$ . Streamer propagation velocity just before flashover is measured and the influence of several parameters such as gas nature and pressure, polarity and electrode geometry are investigated.

## 2 EXPERIMENTAL ARRANGEMENT

The experimental device consists of a grounded metallic test cell, connected by a bushing to a high voltage impulse generator and a voltage divider, as well as a data acquisition system (Figure 1). The used test cell is similar to the one presented in [15]; it is able to handle internal gas pressure up to 9 bar ( $10^5$  Pa) absolute. It contains a high voltage (HV) electrode connected by a bushing and a grounded electrode; both are made of aluminum. The cylindrical solid sample is placed between them (Figure 2). The electrodes (i.e., their shape) are designed to avoid the electric field reinforcement around the triple point, at the junction between the electrodes and the solid insulator. The HV electrode is drilled to be able to put a metallic needle with a controlled tip radius.

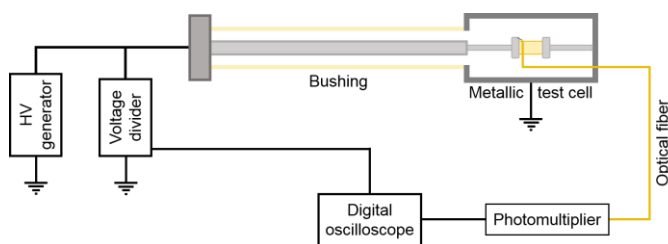


Figure 1. Schematic diagram of the experimental setup.

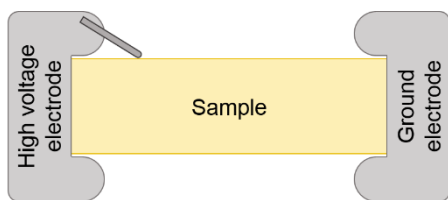


Figure 2. Electrodes and cylindrical sample disposition.

The samples are cylinders of 65 mm in length and 25 mm in diameter. They are made from alumina-filled epoxy resin and are molded in order to have the same surface state as GIS spacers: only the two ends of the cylinders, in contact with the electrodes, are machined. The metallic needle, part of the HV electrode, is made of tungsten, chosen for its high melting temperature ( $3422^\circ C$ ), to avoid deteriorations caused by the pre-breakdown partial discharges. For the majority of the studied cases, the tip radius is  $250 \mu m$  and it is in contact with the solid sample (triple point). However, some cases are tested with smaller tip radii of  $50$  and  $100 \mu m$ , or with a gas gap between the electrode and the solid insulator sample. These particular cases are gathered under the

name “Tip influence” in Table 1 and are specified when presented. The total creepage length between the tip and the ground electrode is approximately 50 mm. To avoid the influence of markings or deformations, the solid insulator sample and the tip electrode are both replaced after each flashovers series.

Standard lightning impulse voltages ( $1.2/50 \mu s$ ) of positive and negative polarity, defined by the IEC 60060-1, are supplied by a Marx generator. The applied voltage is measured using a high voltage divider, connected to an oscilloscope.

The light activity at the tip electrode is observed by the open end of a broad-spectrum optical fiber ( $180-1200$  nm), oriented toward the high voltage tip electrode, so as to detect only the light in the vicinity of the tip. The optical signal is transmitted to a photomultiplier (PM) Hamamatsu H10721-113 ( $185-700$  nm). The resulting electrical signal is measured thanks to an oscilloscope.

Two different gases are investigated: pure  $SF_6$  used as reference gas and a  $6\% C_4F_7N / 84\% CO_2 / 10\% O_2$  gas mixture. The  $6\%$  ratio of  $C_4F_7N$  was chosen equal to one used in existing GIS system using the  $C_4F_7N/CO_2/O_2$  mixture [16], allowing its use at temperature down to  $-25^\circ C$  without liquefying. For this ratio, the dielectric withstand in the mixture without solid is approximated to 0.86 times those of  $SF_6$  at equal pressure, under uniform electric field [3]. About the  $O_2$  content, used to reduce the carbon decomposition products in gas-insulated switchgears, its ratio was fixed at the maximum value that shows no influence on dielectric parameters [8].

For  $SF_6$ , only one pressure of 5.5 bar absolute is used; this corresponds to a typical pressure inside GIS. For the  $C_4F_7N/CO_2/O_2$  mixture, three pressure levels are studied: 5.5, 7.5 and 8.2 bar absolute. They correspond respectively to: (1) the same pressure as that with  $SF_6$  for an equal-pressure comparison, (2) the minimum pressure found in installed GIS using  $C_4F_7N/CO_2/O_2$  mixture [16] and (3) the theoretical equivalent pressure of 5.5 bar of  $SF_6$  for this  $C_4F_7N$  ratio, previously estimated in a divergent geometry [3]. An overview of the studied experimental conditions are presented in Table 1.

Table 1. Overview of the experimental conditions tested.

Gas	Experimental conditions				
	LI+			LI-	
$SF_6$	5.5 bar				
$6\% C_4F_7N / 84\% CO_2 / 10\% O_2$	5.5 bar	7.5 bar	Tip influence 7.5 bar	8.2 bar	7.5 bar

## 3 MEASUREMENT METHOD

### 3.1 VOLTAGE APPLICATION PROTOCOL

The voltage application method is the same for all the experimental conditions. After the sample positioning and gas filling, several standard lightning impulses ( $1.2/50 \mu s$ ) are applied. The first voltage applied is 20 kV (resp.  $-20$  kV for negative polarity); for the following impulses, the voltage is increased by 5 kV steps, until flashover. A waiting time of one minute is held after each impulse. After the first flashover, additional impulses are applied at the same voltage value in order to get at least three flashovers on the sample. Even though the surface condition is

changed, this allowed gathering extra data under the same gas conditions.

To avoid the influence of surface marks on the solid insulator caused by flashovers, the sample is replaced for each experimental condition. The erosion of the tip radius is observed after flashover and the needle is changed when necessary.

### 3.2 PHOTOMULTIPLIER MEASUREMENTS

The open extremity of the optical fiber is placed to collect the light emitted at the high voltage tip electrode. The photomultiplier is then able to measure this light. The system is configured to record the light emitted when the flashover occurs, using an electrical attenuator to avoid the saturation of the signal. An example of signal given by the photomultiplier is presented in Figure 3, with the corresponding measured voltage. Note that the oscillations observed on the rising front of the applied voltage are due to unavoidable parasitic inductances of the measuring circuit. However, the applied voltage still complies with the IEC 60060-1 standard.

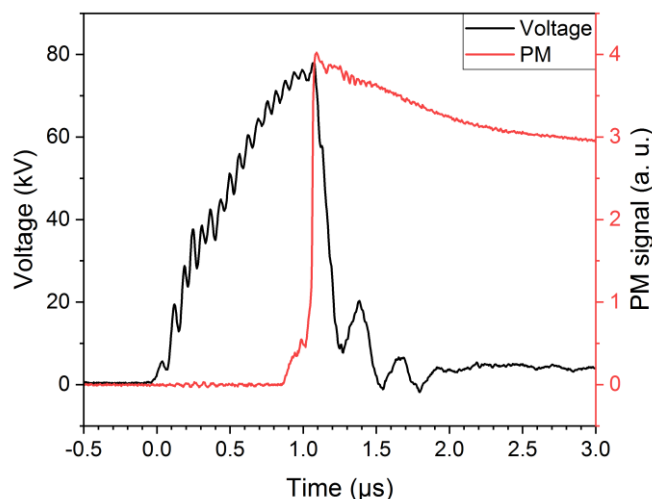


Figure 3. Example of voltage and photomultiplier signals measured at flashover.

The shape of the photomultiplier signal is reproducible; it is very similar in the numerous experimental conditions. Various steps can be observed in this signal. The instant of the photomultiplier peak value matches the beginning of the voltage drop. This event corresponds to the flashover, i.e. to the establishment of a conductive channel between the electrodes, leading to a loss of electrical insulation in gas and a voltage drop to zero.

Figure 4 presents the same signal as that in Figure 3, with an adjusted scale to observe the transition period. The PM signal can be decomposed in four distinct phases during a flashover.

- ① Signal remains around 0: no activity around the tip electrode.
- ② Signal is not null and starts to rise: a luminous activity is measured around the tip electrode; the streamer discharge appears and spreads.
- ③ Steep slope appears on the signal: the conducting channel is established; the current rapidly increases, rising the gas temperature in the canal and the emitted light.

- ④ Luminosity starts to decrease: the circuit discharges through the short circuit caused by the arc channel, the circulating energy slowly decreases until extinction.

The PM signal is used to compare the propagation velocities of the streamers leading to flashover, for the various experimental conditions. In order to do this, the delay between the signal first appearance and the peak value is measured, matching the duration of the steps ② and ③ of Figure 4. It corresponds to the time between the start of a streamer activity around the tip electrode and a fully established conducting channel, when the streamer reaches the ground electrode on the other side of the sample. Knowing the total creepage distance, the mean velocity of the streamer can be estimated.

Notice that in phase ①, the recorded light emitting signals is so smooth (around 0) because of the initiation time delay. Once the discharge initiated, immediately the flashover occurs. Due to the high speed of the discharges, it is difficult to follow all the stages of its propagation with the used experimental means.

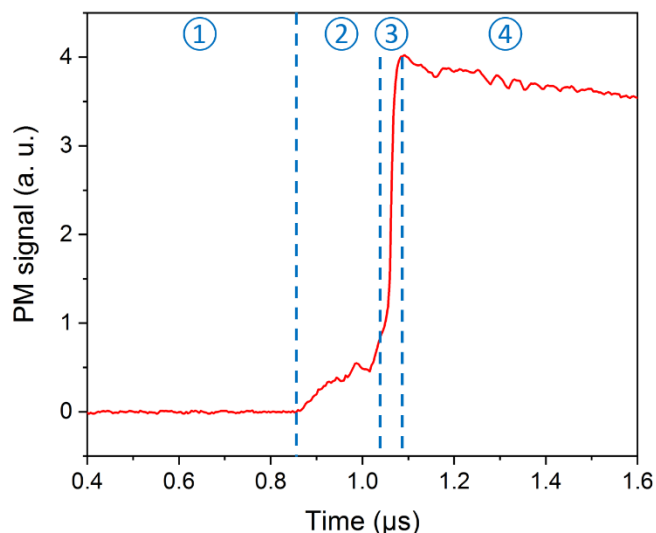


Figure 4. Various steps of the photomultiplier signal measured at flashover.

## 4 EXPERIMENTAL RESULTS

As described by the protocol, for each experimental condition every sample is subjected to a minimum of three flashovers. These flashovers tend to cause markings over the solid insulator, changing the surface condition.

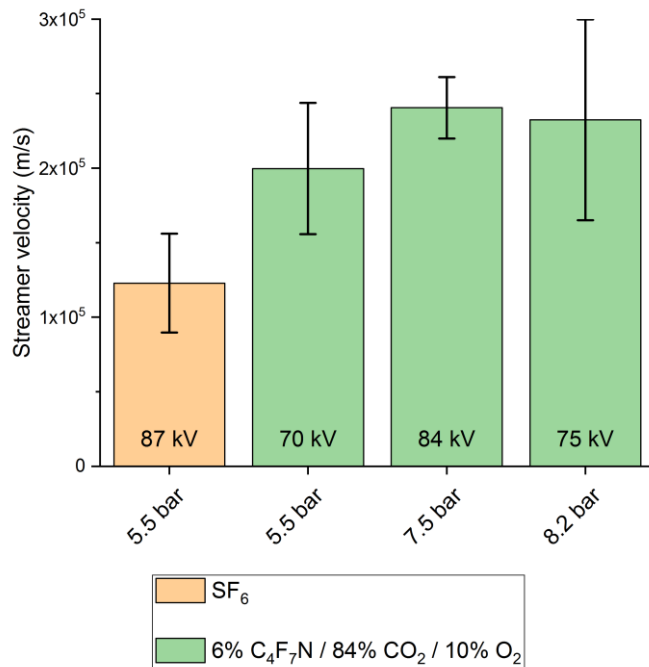
However, for the streamer velocities measurements, no noticeable difference is observed between the first flashover and the following ones. The various results presented therefore show the mean values of the measured velocities, as well as the standard deviation of the results.

### 4.1 INFLUENCE OF GAS

Under positive lightning impulses, streamers velocities are measured on solid insulator surface in  $\text{SF}_6$  and  $\text{C}_4\text{F}_7\text{N}/\text{CO}_2/\text{O}_2$  mixture at various pressures. Figure 5 presents a comparison of both gas/mixture at different pressures; the voltages indicated inside the columns correspond to the mean flashover voltages.

Streamers velocities in  $\text{SF}_6$  are estimated between  $1 \times 10^5$  and  $1.5 \times 10^5$  m/s; these are around 2 times faster in the  $\text{C}_4\text{F}_7\text{N}/\text{CO}_2/\text{O}_2$

mixture, showing a clear influence of the gas nature on the streamers velocity. The fact that the streamer velocity is higher in  $C_4F_7N/CO_2/O_2$  mixtures than that of in  $SF_6$  can be due to the electrical charge at the streamer channel head, which is higher in  $C_4F_7N/CO_2/O_2$  mixtures, this charge resulting of the different ionization rates and different space charge density deposits on the solid surface. Indeed, according to the results reported by Nechmi et al. [17], the 6.7%  $C_4F_7N$  gas mixture has a dielectric strength of about 77% of that of pure  $SF_6$  gas. Therefore, the effective ionization rate in the investigated gas mixture will be higher than that in  $SF_6$ , which will result in a higher density of charge carriers (especially electrons). In consequence, the electrical field at the tip of streamer filaments will be enhanced, what promotes the propagation of the streamer. Thus, the streamer velocity will be higher in the mixture. Note that although  $CO_2$  is a slightly attaching gas, its attachment ability is not reflected when mixed with the alternative gases [5]. With a similar geometry in air over PTFE, Allen and Faircloth [18] measured streamers velocities of the same order of magnitude, between  $4 \times 10^5$  and  $8 \times 10^5$  m/s.



**Figure 5.** Mean streamers velocities measured under positive lightning impulses in  $SF_6$  and  $C_4F_7N/CO_2/O_2$  mixture at various pressures. Error bars correspond to the standard deviations. The voltage values indicated inside the columns correspond to the mean flashover voltages.

On the other hand, the solid dielectric surface can modify the ionization and attachment mechanisms, either by electrons emission caused by photons bombardment or by electrons attachment to surface traps [19]. The species (ions, electrons) resulting of the ionization/attachment processes in the gas also influence the charge deposited on the insulating surface and hence the electric field, especially at the head of streamer.

Several studies indeed showed that for a fixed geometry in air, the streamer propagation velocity can double depending on the solid material used [20, 21]. For our study, a single solid material is investigated and all the samples are made under the same conditions, to ensure that only the gas influence is analyzed. Okubo et al. [9] observed discharges propagation velocity variations

depending on the  $SF_6$  ratio in several  $N_2/SF_6$  mixtures. Streamers propagation in gas is associated with charges motion in the environment: their velocities are linked to that of the charges, especially electrons. The electrons mobility depends, among others, on the electric field and the dielectric gas nature and pressure [22]; the physicochemical characteristics of  $SF_6$  being well known [23].

However, for the  $C_4F_7N/CO_2/O_2$  mixture, as it is relatively a new dielectric gas and contains several chemical species, these values are more complex to evaluate. Consequently, the theoretical interpretation of the gas nature influence on streamer propagation remains difficult with the currently available results.

The average flashover voltages obtained during the experiments are displayed inside columns of Figure 5 for comparison. From these values, it remains difficult to draw conclusions about the relation between streamer velocities and flashover voltages. Besides, the first goal of these experiments was not to determine flashover withstand values; more samples are needed for this purpose. Thus, the flashover voltage values presented have to be taken carefully.

Concerning the gas pressure influence on the streamers velocity, three different levels of 5.5, 7.5 and 8.2 bar are investigated in the  $C_4F_7N/CO_2/O_2$  mixture. According to the obtained results, the pressure does not seem to have a significant influence on the streamers propagation velocity in this mixture. A slight increase in the mean value is observed between 5.5 bar and 7.5 bar, but there is no variation between 7.5 bar and 8.2 bar. Only the results dispersion seems to vary with the pressure, but no tendency can be drawn. Note that the values of pressure are in bar absolute.

## 4.2 INFLUENCE OF POLARITY

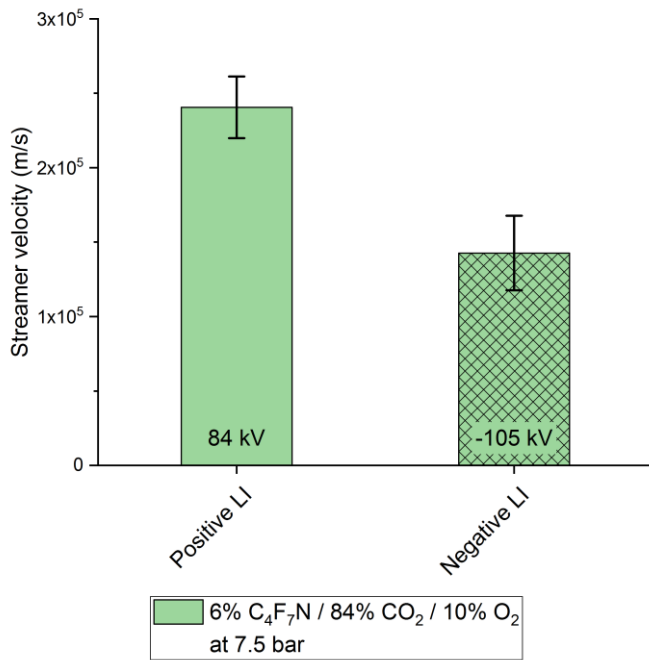
To observe the influence of polarity, the streamers velocities are measured in the  $C_4F_7N/CO_2/O_2$  mixture at 7.5 bar under positive and negative polarity. The results are presented in Figure 6. Streamers measured under negative lightning impulse are around 60% slower than under positive polarity.

With a positive tip, electrons are collected by the high voltage electrode and the positive space charge at the streamer head progresses along the surface in the direction of the ground electrode. In the gas alone, the electrons useful for the streamer propagation are mainly produced by photoionization of the surrounding gas molecules. The presence of a solid insulator surface can then be an additional electron source resulting of photoionization [19, 24] and possibly support the discharge development (Figure 7).

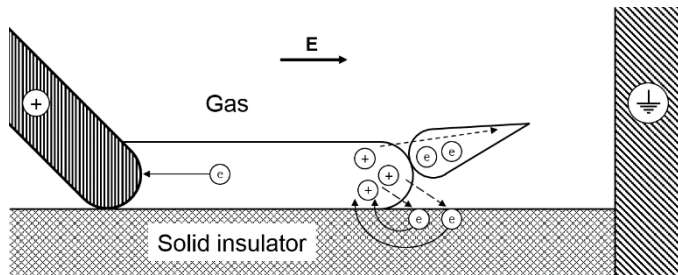
The effect of a solid insulator on the positive streamer propagation velocity has been reported in [20]. The measured discharges are faster with a solid insulator surface than in the gas alone, suggesting the acceleration of the positive surface discharge by the solid insulator.

On the other hand, with a negative tip, the electrons useful for the discharge propagation are directly emitted by the high voltage electrode. One of the hypothesis would be that the traps on the solid insulator surface capture a part of these electrons during the discharge development and slow its progression. The surface accumulation of negative charges can also reduce the electric field reinforcement around the tip electrode: the electric field effect on discharge development is then reduced. These mechanisms could

justify the reduction of streamer propagation velocity under negative polarity compared to positive polarity.



**Figure 6.** Mean streamers velocities measured under positive and negative lightning impulses in the  $C_4F_7N/CO_2/O_2$  mixture at 7.5 bar. Error bars correspond to the standard deviations. The voltage values indicated inside the columns correspond to the mean flashover voltages.



**Figure 7.** Surface discharge development under positive polarity (adapted from [24]).

Note that the influence of the polarity and the geometry of the electrodes on the propagation of the surface discharge over the solid insulator in  $SF_6$ ,  $CO_2$ ,  $N_2$  and their mixtures has been widely studied. However, to our knowledge, the influence of these parameters on the surface discharges in the  $C_4F_7N/CO_2/O_2$  mixture has never been reported in the literature. These results show a propagation mechanism similar to those of other insulating gases such as  $SF_6$ , ensuring a near discharge propagation mechanism using this new gas mixture.

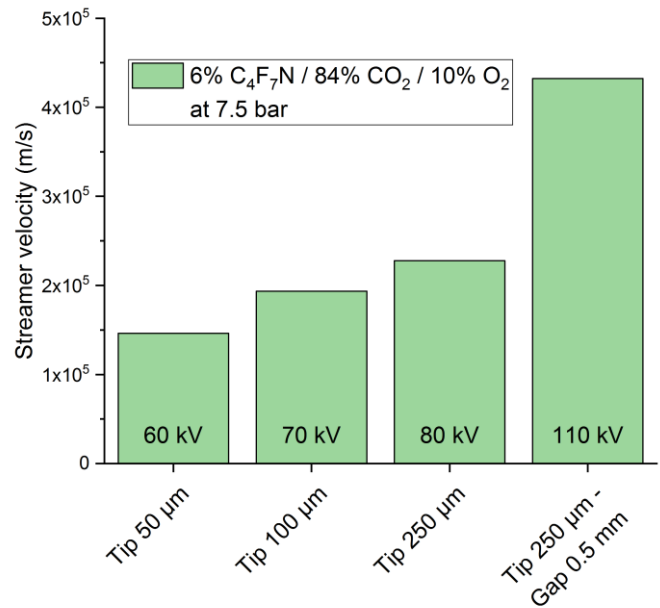
### 4.3 EFFECT OF THE TIP ELECTRODE GEOMETRY

For the influence of the geometry of the tip electrode, no mean value is presented as only the first flashover on each sample is taken into account. It was observed that for the small tip radius, flashover tends to deform the tip aspect. Hence, its radius cannot be ensured for the following measurements.

The results obtained in the  $C_4F_7N/CO_2/O_2$  mixture at 7.5 bar are presented in Figure 8. The three first bars represent various tip radius for the high voltage electrode, with the tip in contact with the solid insulator surface; and the last bar corresponds to the case with a standard electrode tip radius (i.e. 250  $\mu m$ ) and a gas gap of approximately 0.5 mm is present between the tip and the solid insulator sample. The third case, with a tip radius of 250  $\mu m$  in contact with the solid insulator sample, is the reference standard case, used for all the other measurements.

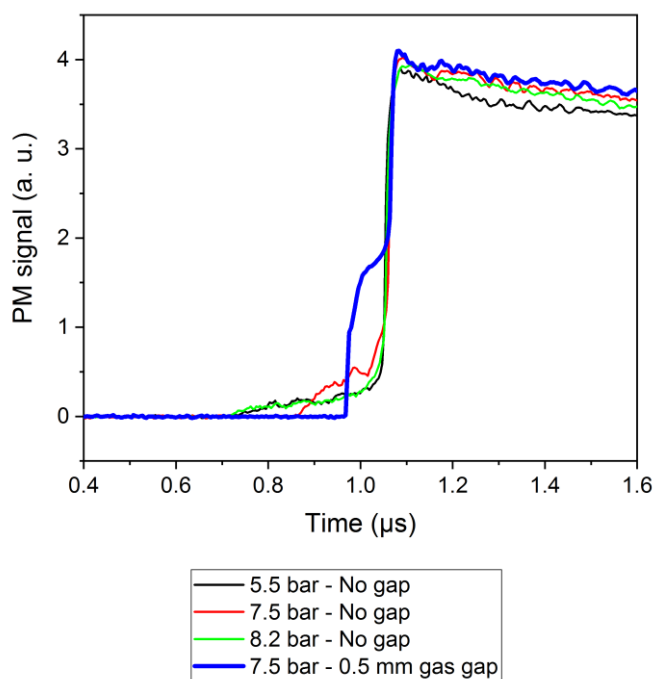
For the cases where the tip electrode is in contact with the solid insulator, the streamer velocity increases with the tip radius: the sharper the tip, the slower the streamer is. This is due to the fact that when the radius of curvature of the tip increases, the initiation threshold voltage of streamers increases so that the field reaches the value of the electrical threshold voltage of streamers. Thus, the streamer being initiated at higher voltages, the flashover voltage will be higher. In the presence of a gas gap and for equal tip radius, the streamer velocity doubles compared to the triple point case.

Besides the streamer velocity increase, the gas gap also causes a different photomultiplier signal shape, as presented in Figure 9.



**Figure 8.** Streamers velocities measured during the first flashover in the  $C_4F_7N/CO_2/O_2$  mixture at 7.5 bar, under positive lightning impulses, for various tip electrode conditions. The voltage values indicated inside the columns correspond to the flashover voltages.

Compared to the typical shape showed in Figure 4, that presented a 4-steps shape, two steep slopes are observed with a gas gap. This effect can be attributed to the variation of the initiation environment. With a gas gap, the initiation takes place in gas alone before reaching the solid insulator surface. In this area, the electric field is mainly normal, suggesting a first propagation normal to the solid insulator, from the tip to the sample. That could explain why the first slope is different to the one observed with a triple point. In this latter case, the initiation starts directly on the solid surface. However, the second slope is similar for both cases (with and without contact), suggesting that the propagation is the same during the second step.



**Figure 9.** Photomultiplier signal of the first flashover obtained in the  $C_4F_7N/CO_2/O_2$  mixture under positive lightning impulse, with a  $250\ \mu m$  tip radius electrode for three cases with the electrode in contact with the solid sample (no gas gap) and several gas pressures are compared to a last case with a  $0.5\ mm$  gas gap.

These results on the influence of the tip electrode geometry in the  $C_4F_7N/CO_2/O_2$  mixture show that the estimated streamer propagation velocity increases with the enhancement of the local electric field. The electric field around the tip electrode is indeed reinforced by the triple point [25] or by the diminution of the tip radius. It appears from the above experiments that these two effects seem to reduce the streamer propagation velocity during flashover.

## 5 CONCLUSIONS

By measuring the light emission around the high voltage tip electrode during flashover on epoxy insulator samples, the propagation velocity of surface streamers under lightning impulse was estimated. The results obtained in an  $6\% C_4F_7N / 84\% CO_2 / 10\% O_2$  gas mixture were compared to  $SF_6$ , and the influence of gas pressure, voltage polarity and geometry of the high voltage tip electrode was presented.

Under the same conditions, the streamers velocities were measured around 2 times faster in the  $C_4F_7N/CO_2/O_2$  mixture than in  $SF_6$ , indicating the strong influence of gas nature on the streamer propagation. No influence of the mixture pressure was however observed.

Concerning the influence of polarity, it was observed in the  $C_4F_7N/CO_2/O_2$  mixture that the surface streamer propagation under negative polarity is around 60% slower than under positive polarity. This could be caused by the variation with the polarity of the electron production mechanisms around the solid sample. In presence of a solid insulator near the streamer channel, its propagation is more assisted with a positive high voltage electrode.

For the first flashover streamer propagation, an influence of the high voltage electrode geometry was also noted. It was observed that the presence of a triple point or a diminution of the high voltage

electrode tip radius, causing an electric field reinforcement, resulted in a diminution of the streamer propagation velocity. The photomultiplier measurements also showed a difference in the light signal emitted at the tip electrode in presence of a gas gap between the electrode and the solid sample (no triple point). The streamer propagation mechanisms seem to vary according to the triple point presence.

## ACKNOWLEDGMENT

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