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Pre-breakdown streamer phenomena in CO₂, Air, and their mixtures, and transition to leader

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Abstract - In this study, pre-breakdown phenomena in CO₂, air, and air/CO₂ mixtures are characterized under positive voltage impulses. A point-plane geometry (tip radius of curvature: 0.2mm, inter-electrode distance: 50mm) is used to generate a divergent electric field and facilitate discharge inception. Breakdown voltage measurements and time-resolved discharge characterization are performed for pressure between 0.1 MPa and 0.5 MPa. In air, breakdown results from streamer propagation up to 0.4 MPa, followed by a transition to the leader mode for higher pressures. CO₂ shows a similar transition above 0.2 MPa, and the mixtures have an intermediate behavior.

I. INTRODUCTION

Sulfur hexafluoride (SF₆) gas, which is electronegative and shows a high breakdown voltage, has been widely used since several decades for high and medium voltage equipment insulation, and for current interruption in circuit breakers and switches. However, it has a very high environmental impact as a greenhouse gas, with a global warming potential of around 24000 (1kg of SF₆ is equivalent to 24 tons of CO₂), and a lifetime of 3200 years [1]. Since the amount of SF₆ in the atmosphere continues to increase, alternatives are being sought to replace it. In recent medium voltage equipment, only the insulation function is studied, the current breaking being assured by vacuum interrupters. Among the various alternatives considered, HFO (Hydrofluoro-Olefin) gas shows a breakdown voltage comparable to that of SF₆, but has been discarded because of the production of solid by-products (soot) under the effect of discharges [2]. Air is also considered as a promising alternative, but its breakdown voltage being about three times lower than SF₆ in typical conditions, it is necessary to increase its pressure P according to the required operation voltage (typically up to 0.2 to 0.3 MPa). In our study, the influence of CO₂ addition to air is presented. This gas could increase the breakdown voltage of air due to its electronegativity.

This article deals with the analysis of pre-breakdown phenomena in air/CO₂ mixtures. A lot of work has been done to study these mechanisms in air and SF₆, but few data are available for air/CO₂ mixtures, under representative conditions of medium voltage applications: gap distances of several centimeters and pressures from 0.1 to 0.3 MPa. In electronegative gases such as SF₆ or HFO, breakdown is due to the propagation of “leaders”, consisting of a few highly ionized and conductive channels. They propagate in successive jumps,

and the breakdown occurs immediately when they reach the opposite electrode [3]. In air at atmospheric pressure, breakdown occurs by a distinct mechanism of “streamer”, with many filaments, dimly luminous and poorly conducting [4].

The streamer and leader mechanisms exist in all studied gases (SF₆, HFO, air), but under various conditions of pressure, voltage, and gap distance d . For example, in a point-plane geometry with $d = 5$ cm, the transition from streamer breakdown to leader breakdown occurs at a low pressure $P = 0.03$ MPa in HFO and 0.05 MPa in SF₆ [2], and much elevated in air (0.5 MPa, see below).

In this paper, an experimental study is performed to characterize the pre-disruptive phenomena in air/CO₂ mixtures. A point-plane geometry with a fixed distance $d = 5$ cm is used to strongly favor the inception of pre-disruptive phenomena over a wide range of pressure and voltage, to study their propagation. These experiments are performed under positive high voltage impulse. The pre-breakdown mechanisms are characterized for different pressures, from high-speed photography, measurements of breakdown voltages, transient currents, light emission, as well as propagation velocities. As the electrode geometry is very different from the one present in an industrial system, the breakdown voltage measurements obtained here are not directly transposable for switchgear design. On the other hand, the characterization of pre-disruptive mechanisms in the different gases and mixtures allows better understanding, interpretation, and extrapolation of their breakdown properties in more realistic situations.

II. EXPERIMENTAL METHODS

A. High Voltage Test cell

A Marx generator is used to generate a positive voltage impulse (0.9 μ s / 1400 μ s) with a rise time of 0.9 μ s and a fall time of 1400 μ s at 50% of the peak voltage. The divergent electric field is produced with a point electrode with tip radius of curvature $R_c = 0.2$ mm, located at a distance $d = 50$ mm from a plane of 100 mm diameter (Fig. 1). This system provides a high field enhancement factor $\eta = 70$ ($\eta = \text{maximum field} / \text{average field}$). This favors the study of propagation mechanisms, by causing a stable, reproducible discharge inception with a low delay. In contrast, in a real industrial system the field is less divergent ($\eta < 10$), which significantly changes the conditions of discharge inception.

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B. Discharge Characterization

The voltage is measured by a capacitor divider connected to the Marx generator. The transient pre-discharge current is measured directly on HV electrode connected to the high voltage, via a $5\ \Omega$ resistor in series, coupled with a 100 MHz analog electro-optical transmitter (Fig. 1). By using a shielded electrode holder, only the current flowing through the point extremity is obtained. With this arrangement, the electrode charging current flowing during the voltage rise time is limited to some mA. This makes it easy to detect and measure pre-breakdown currents superposed on this low charging current [2].

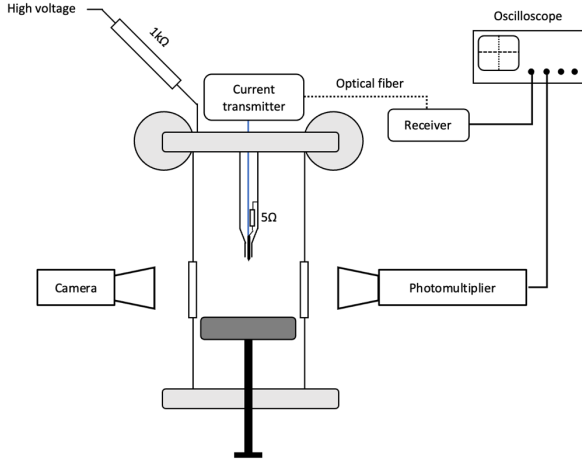


Fig. 1. Experimental system used.

A photomultiplier (PM, PhilipsTM 56AVP, spectral response 300-600 nm) records the discharge light emission with a resolution of a few nanoseconds, through a quartz window. A fast gated intensified camera (HamamatsuTM C9546-03, spectral response 150-800nm; Intensifier: HamamatsuTM 2803) allows to obtain photographs of pre-discharges. Using the “deskew” function of the oscilloscope, precise delays were added to all channels in order to obtain perfectly synchronized measurements of light, current, voltage, intensifier opening, with a maximum synchronization error about 1 ns. Due to the fiber optic and PM measurement system, currents and light intensity appear as negative signals on the recordings.

III. EXPERIMENTAL RESULTS

Different measurements were carried out for the characterization of pre-breakdown phenomena. First, a measurement of breakdown voltage versus pressure was performed in air, CO₂, and different mixtures. Then, a time-resolved analysis of the pre-breakdown phenomena was undertaken.

A. Breakdown voltage of air, CO₂, and air/CO₂ mixtures

Fig. 2 shows the variation of breakdown voltage V_b versus pressure P (absolute pressure) for air, CO₂, and two mixtures M⁵⁰ (50% air / 50% CO₂) and M²⁰ (80% air / 20% CO₂). These measurements are compared to those obtained in SF₆ and HFO

under identical conditions [2], and show different variations depending on the gas nature.

In air and CO₂, V_b increases significantly up to some pressure value (air: 0.4 MPa, CO₂: 0.2 MPa), and then slowly decreases for higher pressures. For $P \leq 0.2$ MPa V_b is comparable in both gases, becoming thereafter significantly higher in air at higher pressures. In mixtures, a comparable variation is observed, with a “transition” pressure of 0.2 MPa for M⁵⁰ and 0.3 MPa for M²⁰. The addition of CO₂ to air causes a slight increase in V_b at low pressure (about +5% for $P \leq 0.2$ MPa), and conversely a marked reduction at higher pressures. This reduction is as more marked as the amount of CO₂ is higher (for example -15% at 0.3 MPa in the case of M⁵⁰).

It is known that streamer propagation is strongly influenced by pressure, which explains the increase of the breakdown voltage in point-plane geometry when P is raised. However, when the pre-breakdown phenomenon becomes a leader, the pressure no longer has a significant effect on the propagation, and consequently on the breakdown voltages in the point-plane geometry [6][7]. The plots obtained here are consistent with these observations:

- below the “transition” pressure (dotted line) the breakdown is of the “streamer” type (this will be confirmed by visualization);
- above this pressure (plots in solid lines) the breakdown becomes of “leader” type.

Adding CO₂ to air favors the transition toward a leader type breakdown, depending on the amount of CO₂ added: the breakdown behavior of M⁵⁰ mixture is close to CO₂, the M²⁰ mixture is intermediate between air and CO₂.

Concerning the breakdown voltage V_b in divergent geometry, the addition of CO₂ thus causes contradictory effects depending on the breakdown mechanism:

- slightly favorable at low pressure, by making streamer propagation more difficult;
- unfavorable at high pressure, by favoring the appearance of leaders.

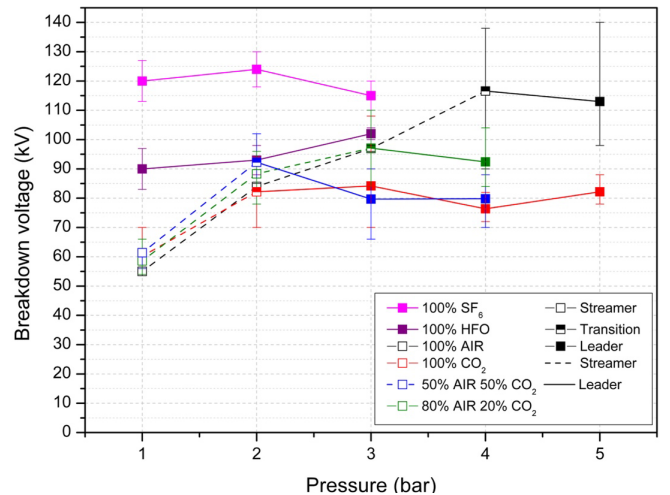


Fig. 2. Breakdown voltage versus pressure in air, CO₂, and mixtures with 20% and 50% CO₂, and comparison with SF₆ and HFO [2]

The comparison with SF₆ and HFO (in which breakdown is due exclusively to leaders in the considered pressure range), shows that leaders in CO₂ form and propagate more easily than in these electronegative gases: breakdown voltages due to leaders at 0.2 and 0.3 MPa are significantly lower in CO₂.

B. Photographs, transient currents, and light emission of streamers and leaders

In this section, photographs of streamers and leaders, together with transient current and light emission measurements, are shown for air (Fig. 3), CO₂ (Fig. 4), and M²⁰ mixture (Fig. 5. 80% air / 20% CO₂).

In air, we observe highly ramified streamers (Fig. 3A, obtained with $P = 0.2$ MPa). The streamer is composed by numerous low conductivity plasma channels, whose temperature is close to 300 K. A single fast current pulse (duration of a few tens of ns) is associated with the propagation. At low pressure (as in Fig. 3A), the streamer propagates to the plane, but breakdown does not occur. It is necessary to further increase the impulse voltage to observe breakdown. When the pressure is increased at a fixed voltage, the maximum streamer size decreases (many streamers no longer propagate to the plane). It is then necessary to increase the impulse voltage to observe the propagation to the plane. With $P = 0.4$ MPa, breakdown occurs as soon as the streamer reaches the plane.

Fig. 3B, obtained for $P = 0.5$ MPa, shows the pre-breakdown phenomenon changed to a leader, characterized by a single bright channel. The leader head, consisting of a streamer, is also clearly visible in this gas. In all recordings, a streamer is first observed (first current and light impulse in Fig. 3B), followed by the propagation of the leader (which occurs here after a delay of about 5 μs), immediately followed by breakdown. During leader propagation, several current and light impulses are observed.

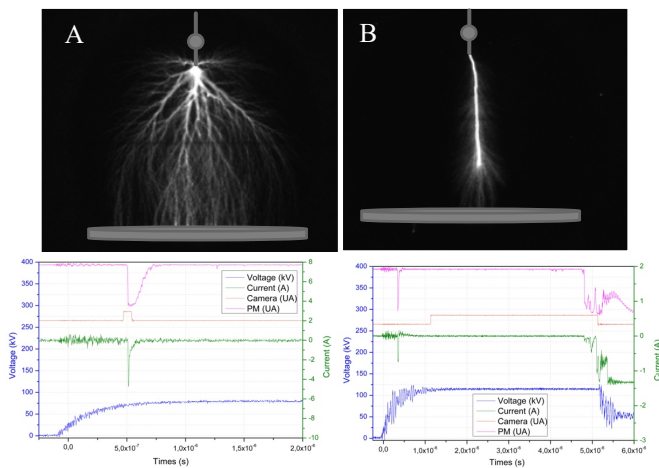


Fig. 3. Pre-breakdown phenomena in air, and associated transient currents and light emission:
 - A : streamer (0.2 MPa, 80 kV)
 - B : leader (0.5 MPa, 116 kV)

In CO₂ (Fig. 4), a distinct behavior is observed in comparison with air. First, streamers touching the plane without subsequent

breakdown are almost never observed. Second, the extension of streamers is smaller than in air (Fig. 4A). The breakdown voltage at low pressure becomes identical to the voltage required for streamer to propagate up to the plane.

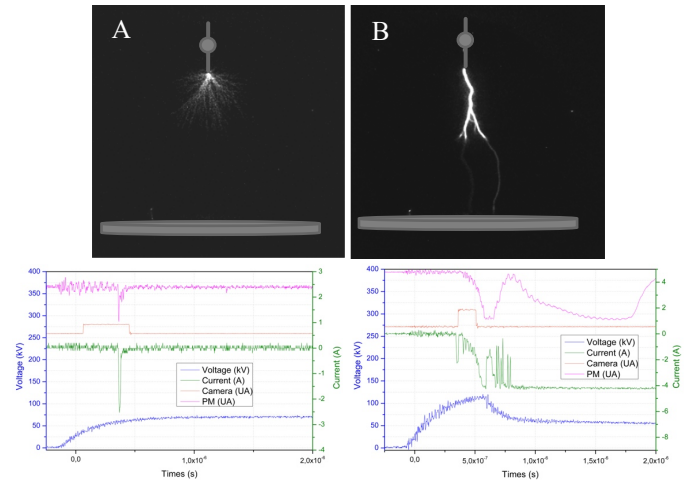


Fig. 4. Pre-breakdown phenomena in CO₂, and associated transient currents and light emission:
 - A : streamer (0.1 MPa, 70 kV)
 - B : leader (0.5 MPa, 130 kV)

Leader breakdown in CO₂ (Fig. 4B) also consists of an initial streamer, followed by leader propagation with multiple current pulses, which immediately results in breakdown. The delay between the initial streamer and the leader propagation is much shorter than in air (< 1 μs on Fig. 4B).

Regarding mixtures, the one including 20% CO₂ (M²⁰) presents visual features relevant of air and CO₂. Streamers are less developed and less luminous than in air. Conversely, leaders show a channel width close to the air, with a weaker luminous intensity like in CO₂. The streamer at the head of leaders is still observable, but less developed than in air.

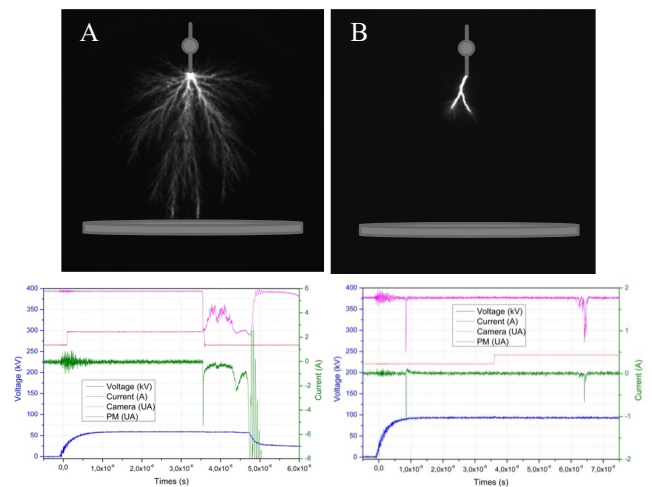


Fig. 5. Pre-breakdown phenomena in mixture M²⁰, and associated transient currents and light emission:
 - A : streamer (0.1 MPa, 60 kV)
 - B : leader (0.4 MPa, 94 kV)

C. Propagation velocities of streamers and leaders

Propagation velocities v were calculated from $v = \frac{L_p}{T_p}$, with L_p : propagation length and T_p : propagation time. For streamers, the propagation duration (a few nanoseconds) was measured from the transient current duration, and the length from photographs. Considering that leaders in air and CO₂ almost systematically lead to breakdown, their propagation time T_p was measured from the inception instant (i.e. initial streamer) to the breakdown instant, and the length corresponded to the gap distance $d = 5$ cm.

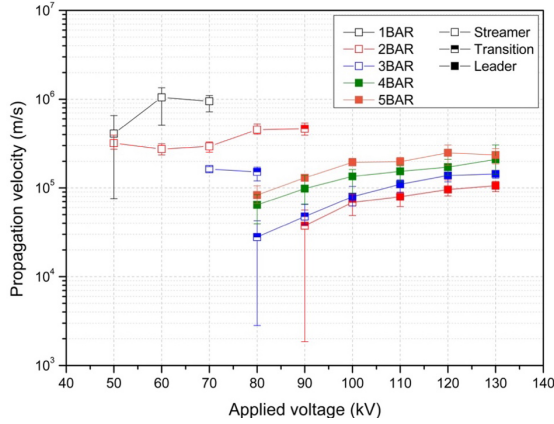


Fig. 6. Propagation velocity versus applied voltage and pressure for CO₂

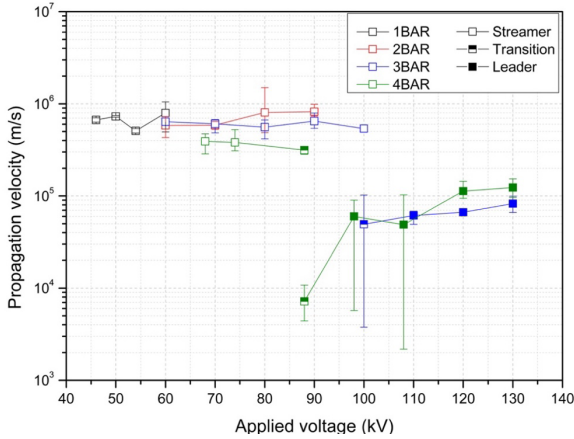


Fig. 7. Propagation velocity versus applied voltage and pressure for M²⁰ mixture.

In CO₂ (Fig. 6), the transition from streamers to leaders occurs when pressure is above 0.2 MPa, and voltage above 80 kV. The velocity v of streamers decreases as the pressure is increased and is between 2×10^5 and 2×10^6 m/s [8]. Leaders are observed over a wider range of pressure and voltage. Their velocity is lower than with streamers, between 3×10^4 and 2.5×10^5 m/s. It increases when pressure and/or voltage are raised, inducing a decrease of their propagation time T_p . For the distance $d = 5$ cm, T_p typically varied between $0.2 \mu\text{s}$ ($v = 2.5 \times 10^5$ m/s) and $1.7 \mu\text{s}$ ($v = 3 \times 10^4$ m/s). In SF₆ or HFO, the leader velocity was similar and also much lower than with streamers, between 1×10^4 and 1×10^5 m/s [2].

In the M²⁰ mixture (Fig. 7), streamer velocities were between 3×10^5 and 1×10^6 m/s. Leaders appear above $P = 0.3$ MPa and $V = 100$ kV, with velocities v between 5×10^3 and 2×10^5 m/s.

IV. CONCLUSION

This study allowed to characterize and compare the different pre-breakdown phenomena existing in air, CO₂, and two mixtures of these gases, for a point-plane electrode geometry (distance $d = 5$ cm) under positive voltage impulse.

In CO₂, a transition of the breakdown mechanism (streamer to leader) occurs when the pressure is higher than 0.2 MPa and the voltage higher than 80 kV. In air, this transition is observed above 0.4 MPa / 120 kV. Mixtures show intermediate behaviors between these two pure gases. In all cases, the streamer propagation velocities are between 1×10^5 and 1×10^6 m/s, and decrease when pressure is raised. Velocities of leaders are lower, between 1×10^4 and 1×10^5 m/s, and conversely increase when pressure is raised. The breakdown voltage V_b increases significantly versus pressure when breakdown results from the propagation of a streamer, since streamer propagation is hindered by pressure. V_b no longer increases beyond the streamer/leader transition: a slight decrease of V_b can conversely occur. The comparison with SF₆ and HFO shows that at the same pressure, leaders in CO₂ can develop and result in breakdown for significantly lower voltages.

The breakdown voltage measurements in divergent point-plane gap show that the addition of CO₂ to air can have a slightly favorable effect at low pressure (≤ 0.2 MPa) when breakdown results from streamers, and unfavorable at higher pressure by favoring the development of leaders.

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