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Electrical Breakdown Study in CO₂ and CO₂-O₂ Mixtures in AC, DC and Pulsed Electric Fields at 0.1-1 MPa Pressure

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ABSTRACT
In this paper, the results of the experiments performed on electrical breakdown in CO₂ and CO₂-O₂ mixtures in weakly and strongly non-uniform fields generated with impulse (2/160) µs, AC and DC waveforms are presented. In weakly non-uniform fields, the electrical breakdown field approximately follows 11 kV/cm bar when stressed with both AC and DC (positive and negative) waveforms. For positive impulse, the breakdown voltage is higher and the time lag to breakdown is scattered, indicating a lack of starting electrons from CO₂ gas. Furthermore, the breakdown strength of CO₂-O₂ (10-30)% mixtures is investigated. On application of negative polarity impulse, the breakdown strength is significantly higher than positive impulse in the measured pressure range of 0.3-0.7 MPa in strongly non-uniform fields, contrary to that seen during breakdown in weakly non-uniform fields. Breakdown voltage for negative impulse is further enhanced in a mixture of CO₂-O₂ (80-20)%.

Index Terms — CO₂, SF₆, alternate gas insulation, electrical breakdown

1 INTRODUCTION
Sulphur hexafluoride (SF₆) is a gas commonly used in high voltage devices such as circuit breakers, gas-insulated switchgear etc., for insulation and switching applications due to its excellent dielectric characteristics. However, it is an extremely potent greenhouse gas with a GWP (global warming potential) of 23,500 times that of CO₂ [1]. Research is ongoing to find a suitable replacement gas which has a lower ecological footprint while at the same time ensuring satisfactory electric and arc-quenching properties. Of the various alternative gases, CO₂ has the most favourable switching (current interruption) performance [2–5] and is a promising replacement, either in pure form or as gas mixtures with small admixtures such as C₂F₁₀O (fluoroketone) or C₂F-CN (fluoronitrile). This is because an insulating gas should possess characteristics such as high electric strength, low boiling point (for use in cold temperatures), low GWP, be non-toxic, have a high chemical stability, be non-flammable and be non-ozone depleting.

Several studies have been published on breakdown in CO₂. Various parameters such as the effect of surface roughness and dielectric coating [6], the streamer parameters [7], breakdown in non-standard impulse waveforms [8], comparison of swarm and breakdown data [9], breakdown in GIS [10], partial discharge behaviour [11] have been studied. However, in this paper, a comprehensive experimental study is performed on electrical breakdown in CO₂ and CO₂-O₂ mixtures. The CO₂-O₂ mixture is interesting due to the electron attaching nature of O₂ and its potential to prevent carbon soot formation during arcing. Moreover, we compare the differences in breakdown strength for strongly and weakly non-homogeneous fields and highlight the differences between them. The gas is tested with impulse, AC and DC waveforms. Using the breakdown voltages and time lag to breakdown, we explain the differences and effects of varying pulse duration. These tests are performed in the pressure range of 0.1 to 1 MPa, which is the range interesting for commercial electrical apparatus. The results can be used as guidelines for designing HV equipment. Furthermore, this work will serve as reference for our planned experiments to study dielectric recovery in CO₂.

2 EXPERIMENTAL SETUP
The impulse (Imp) tests are performed in the HV lab of Eindhoven University of Technology, The Netherlands and the AC/DC tests are performed in the HV lab of ETH Zurich, Switzerland, respectively. As two different setups were used to measure electrical breakdown, both setups are described in the following sections.
2.1 LIGHTNING IMPULSE SETUP

The setup used for the impulse experiments is schematically depicted in Figure 1. A 500 kV, 15 kJ Marx generator is employed to produce the impulse. It produces a double-exponential waveform with a rise and fall time of 2 µs (peak) and 160 µs (to 50 % of peak), respectively. While the rise time (10-90)% is 0.7 µs, the peak is reached at 2 µs. Figure 2 shows a typical applied voltage waveform and the waveform following a breakdown of the gas under test. While the rise and fall times are not the standard lightning impulse (1.2/50) µs, the applied waveform is similar to it and will be referred to as impulse (Imp.) in this manuscript. An aluminium test vessel having a volume of ~250 l rated to a pressure of 15 bar (1.5 MPa) is used. A home-made, damped capacitive voltage divider with a bandwidth of 3 MHz is used to measure the applied voltage and a LeCroy HDO 4104, 1 GHz oscilloscope, records the signals.

2.2 AC AND DC SETUP

The AC and DC experimental setup is described in brief below, but, has been described in detail in Haefliger et al. [9]. The high voltage is generated by a two-stage cascade test transformer. A 100 kΩ resistor in series with the test vessel limits the current during breakdown. For DC measurements, rectifying power diodes are used and smoothing capacitors are added in parallel to the test gap. A capacitive and resistive divider is used to measure the applied voltage for AC and DC, respectively. A breakdown detection feedback circuit is also employed which turns off the voltage within 40 ms after a breakdown.

2.3 ELECTRODES

Two different types of electrodes are used for the experiments. A rod-plane arrangement provides a weakly non-homogeneous field and the second is a point-plane arrangement which produces a strongly non-homogeneous field. The electrode geometries are depicted in Figure 3.

Weakly non-homogeneous field: A rod-plane electrode was employed for the breakdown experiments to provide a weakly non-homogeneous electric field. The rod (HV) electrode has a diameter of 20 mm and gap distance to the grounded plane electrode is 30 mm. Both the HV and the ground electrode are made from stainless steel. This geometry was chosen because non-homogeneous fields occur more often in real-world applications and to study the effect of pulse polarity on breakdown strength. The geometry will also be used for our future planned experiments on dielectric recovery. The field enhancement factor (FE) is given by the relation:

$$FE = \frac{E_{\text{max}}}{E_{\text{average}}}$$

The field ($E_{\text{max}}$) was determined by COMSOL (FEM) simulation and the field enhancement factor is found to be 3.2.

As each measurement point consists of 50-100 voltage applications, micro-protrusions due to electrode conditioning can act as regions of high electric field and affect the consecutive breakdown values [12]. To prevent the electrode conditioning effect, the surface of both electrodes are treated by electrode discharge machining to get a 40 µm surface finish.

Strongly non-homogeneous fields: For these experiments, the electrode arrangement (Figure 3b) defined by the CIGRE working group (WG) D1.67 is chosen. As breakdown experiments are currently underway using several potential alternative gases (by the WG D1.67) using the same geometry, the results can be directly compared against that of CO₂. A needle having a diameter of 1 mm is attached to a spherical electrode, which has a diameter of 40 mm. The needle-tip used in the impulse and DC setup have a diameter of approximately 100 and 400 µm, respectively and the gap distance between the tip and grounded plane is 15 mm.

For AC and DC measurements, the same electrode geometries shown in Figure 3 are used. However, the grounded electrode had a polished surface.
2.4 TEST METHOD AND ANALYSIS

Impulse measurements: The test process is similar to the up and down test process [13], however, the voltage steps are not constant. An example of the test process is shown in Figure 4.

Each measurement point in the results section is obtained after performing a test series. In each test series, about 50-100 voltage pulses are applied, depending on the scatter in the data. During the tests, an interval of 1 minute is provided between consecutive shots.

To calculate the 50% breakdown value, the data is classified as a binomial distribution (breakdown or withstand) with respect to the peak applied voltage and processed using the generalized linear model regression function in Matlab. The error bars are calculated as shown in Figure 4.

AC/DC measurements: For AC and DC measurements, the voltage is ramped up until breakdown occurs. For AC measurements, a series of 60 breakdowns are performed to calculate the breakdown voltage. The voltage is ramped up at a constant rate of about 3-5 kV/s up to about 80% of the expected breakdown value and then closer to the breakdown value, it is raised at a slower rate of 0.1 kV/s. This process is done using an automated setup and the interval between consecutive breakdowns is about 3 minutes. The breakdown voltages are sorted to find the median and the upper and lower error bars represent the 84.13 and 15.87 percentile values, respectively, according to the method described in [9]. The advantage of this technique is that it does not assume a normal distribution (it is distribution independent).

3 RESULTS AND DISCUSSION

3.1 STREAMER CRITERION

It is known that at pressure-distance (pd) higher than 5 bar-mm, the streamer mechanism of breakdown dominates [14] and the breakdown field can be estimated using the semi-empirical streamer criterion. It is used widely [8, 10–13] in literature to predict the streamer inception voltage which is a prerequisite for breakdown to occur. In this paper, we compare the streamer criterion to the breakdown values determined on application of DC fields up to 0.3 MPa. It will also be used as a prediction for DC breakdown values up to 1 MPa to act as a comparison for breakdown values on application of impulse waveforms. Streamer inception can occur when the streamer criterion is satisfied and is given by the equation:

\[ \int_0^{x_{cr}} a_{eff} \, dx \geq k \]  

Where, \( a_{eff} \) is the effective ionization coefficient, which can be calculated using BOLSIG+ [17]. The Phelps cross-section dataset [18] available in the LXCat repository is used for the calculations. The gap distance is denoted as \( x \) and \( x_{cr} \) is the gap distance at which the field is no longer greater than the critical field of the gas, as it is a non- homogeneous field. The critical field is defined as the electric field where attachment coefficient is equal to the ionization coefficient.

The value of \( k \) in Equation (1) is derived from the logarithm of \( 10^8 - 10^9 \) electrons required for a streamer to form. In literature, there is uncertainty regarding the value of \( k \); different values of \( k \) have been used from 9.15 to 20 [9]. In our calculation we used a value of 13, which was used in previous publications [15, 13] and matched their experimentally determined streamer inception values. The detailed parameters used for the calculation of the streamer criterion can be found in Seeger et al. [15], Also, the effect of electrode surface roughness is ignored. The calculated streamer inception values from streamer criterion are shown in Figure 5 and Figure 6.

3.2 BREAKDOWN IN CO₂ IN WEAKLY NON-HOMOGENEOUS FIELD (ROD-PLANE)

This section is divided into three subsections. The first two sub-sections expound the results and discussions on electrical breakdown strength of CO₂ on application of impulse, AC and DC waveforms. In the latter sub-section, the effect of oxygen addition on applying impulse and AC waveform is studied. These experiments were performed with the electrode arrangement shown in Figure 3a.

3.2.1 BREAKDOWN IN PURE CO₂: RESULTS

Figure 5 shows the 50% breakdown strength of pure CO₂ on application of positive and negative polarity impulse up to 1 MPa. Several observations can be made from it. The 50% breakdown strength of CO₂ on application of positive polarity impulse is higher than that of negative polarity impulse. Similar observation has been reported in [6], [19], where the breakdown tests were performed under various electrode arrangements.

Furthermore, the error bars for positive polarity impulse is higher, which indicates a high statistical scatter of the breakdown process.

In Figure 5, the AC median breakdown strength and the calculated streamer inception voltages are also displayed as a comparison to impulse breakdown and discussed in the following paragraphs.

Impulse ratio is defined as the ratio of impulse to AC breakdown voltage. This is calculated from the median of AC and 50% impulse breakdown values from 0.1 to 0.5 MPa. The average impulse ratio for positive polarity from 0.1-0.5 MPa is calculated to be 1.7 and the minimum and maximum ratios were 1.33 and 1.99, respectively.
It is interesting to note that the breakdown voltage is the same for both positive and negative polarities.

### 3.2.2 Breakdown in Pure CO\textsubscript{2}: Discussions

The DC median breakdown values require marginally higher voltages (~10-15\%) than predicted by the streamer criterion. The difference between calculated streamer inception and measured breakdown values can be attributed to the fact that the streamer criterion predicts the minimum inception values and does not take into effect the starting electron waiting time, the effect of the oxide layer on electrodes, etc. Moreover, there is an uncertainty in the values of \(a_{\text{eff}}\) as various datasets in the LXCat repository have slightly different values, especially at fields higher than the critical field. The value of ‘\(k\)’ used in Equation (2) also influences the calculated inception value. Nevertheless, the streamer criterion provides a good first approximation to the experimentally determined breakdown values and can be used to predict the breakdown values for weakly non-homogeneous fields in AC and DC waveforms.

On comparing the AC (Figure 5) and DC (Figure 6) breakdown voltages for both polarities in pure CO\textsubscript{2}, it is seen that they are almost equal. This is surprising, as for AC, the breakdown occurs only in the negative half-wave (Figure 9). One explanation may be that in the negative half-cycle in an AC waveform (over several cycles) the starting electron is obtained from field emission and leads to a breakdown. However, for DC waveforms due to the slow ramping of voltage (100 V/s), there is enough time even for positive polarity to obtain the first electron from detachment or background radiation and breakdown voltage is equal for positive and negative polarity.

For impulse waveform, a higher voltage than DC/AC is needed for breakdown (Figure 5), with positive breakdown voltages being higher than that for negative polarity. This can be explained by the fact that the pulse length is much shorter (\(\mu\)s timescale), and a higher field is needed for generating sufficient starting electrons required for discharge initiation. It is observed for negative polarity impulse at 0.1 MPa, the minimum breakdown strength is close to the AC breakdown strength. This shows that while impulse breakdown at AC voltage level is possible, it usually occurs at voltage higher than that in AC breakdown field, which is likely due to unavailability of starting electrons in the short timescale. However, when stressed with positive polarity impulse, not only is a higher voltage needed for breakdown, but the error bars of the breakdown strength are also large compared to breakdown in negative polarity. This can possibly be explained by the starting-electron effect.

For a breakdown on application of positive polarity impulse, the first free electron required for an avalanche needs to originate from negative ions, interaction of gas molecules or from the gas itself (background radiation), etc. It also needs to be present in the high field region (critical volume). The critical volume is the volume of the gas which experiences a field greater than the critical field of the gas which can lead to a positive effective ionization in a decaying field. Hence, the electron availability is stochastic and takes time.
time lag with increasing applied voltage and is random. This supports the argument that the lack of the starting electrons is the likely cause of the higher breakdown strength and larger time lag for positive impulse. Further experiments should be done to study the effect of starting electron on breakdown strength and time lag, by irradiating the electrodes with UV-C or a radioactive source to provide the starting electrons.

The observations in this contribution for weakly non-homogeneous fields can be summed up as follows:

- The breakdown strength when stressed with positive and negative DC fields are the same.
- Breakdown occurs in the negative half-cycle of the AC waveform.
- Breakdown occurs at lower voltages when stressed with negative impulse compared to positive (with low standard deviation in the breakdown voltage and short time lag).

These observations, support the argument that starting electrons are readily available when negative field is applied to the rod electrode and has a significant effect on breakdown strength when stressed with pulsed fields.

### 3.2.3 BREAKDOWN IN CO₂-O₂ MIXTURES

While it is well known that the dielectric and current interruption performance of pure CO₂ cannot match that of SF₆, increasing the pressure of the apparatus as well as using CO₂-based mixtures are some techniques to improve its performance. The electron attaching nature of O₂ and its ability to prevent carbon soot formation [2] may be advantageous in HV devices. Therefore, CO₂-O₂ mixtures with O₂ content of (10-30)% are studied.

A study comparing CO₂ and CO₂-O₂ mixtures under homogeneous AC field has been reported by Haefliger et al. [9]. An increase of ~12% and 25% in the breakdown strength of CO₂-O₂ (80-20)% and CO₂-O₂ (20-80)% mixtures, respectively was reported when compared to pure CO₂.

A 17% increase in breakdown strength for CO₂-O₂ (80-20)% in a coaxial arrangement (inner conductor diameter 120 mm and tank diameter of 300 mm) was reported by Uchii et al. [2]. Okubo et al. [20] report a decrease in breakdown strength (compared to pure CO₂) of CO₂-O₂ (50-50)% in a rod-plane geometry (diameter 5 mm, gap = 40 mm) from 0.2-0.4 MPa. An increase in breakdown strength at 0.1 and 0.15 MPa has been attributed to corona stabilization by the authors.

The data from above has been tabulated in Table 1 where FE stands for the field enhancement factor, which was calculated by simulating the fields based on the reported geometry.

<table>
<thead>
<tr>
<th>Source</th>
<th>Field</th>
<th>Electrode arrangement</th>
<th>FE</th>
<th>O₂ ratio</th>
<th>BD ratio (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haefliger[9]</td>
<td>AC</td>
<td>Parallel plane</td>
<td>1</td>
<td>20%</td>
<td>+12%</td>
</tr>
<tr>
<td>Haefliger[9]</td>
<td>AC</td>
<td>Parallel plane</td>
<td>1</td>
<td>80%</td>
<td>+25%</td>
</tr>
<tr>
<td>Uchii[2]</td>
<td>LI</td>
<td>Coaxial</td>
<td>2.5</td>
<td>20%</td>
<td>+17% (1.1 MPa)</td>
</tr>
<tr>
<td>Okubo [20]</td>
<td>LI (+)</td>
<td>Rod-plane</td>
<td>11.2</td>
<td>50%</td>
<td>-10% (0.2-0.4 MPa)</td>
</tr>
</tbody>
</table>

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Therefore, there is an improvement of about 6% (average) in breakdown strength under non-uniform fields up to 0.5 MPa when stressed with AC waveform.

The results for positive and negative polarity impulse waveforms are shown in Figure 9a and Figure 9b, respectively. It can be observed that at all measured pressures, the 50% breakdown voltages are within the error bars and no clear trend can be seen.

On comparing the breakdown strength of CO$_2$-O$_2$ mixtures found in literature (Table 1) which show both higher and lower breakdown strength compared to pure CO$_2$ and our experimental data, it becomes clear that the breakdown strength of CO$_2$-O$_2$ mixtures are dependent on the electrode geometry and pulse duration.

### 3.3 BREAKDOWN IN CO$_2$ AND CO$_2$-O$_2$ (80-20)% IN STRONGLY NON-HOMOGENEOUS FIELDS (POINT-PLANE GEOMETRY)

This section is divided into two subsections. The first subsection entails the results of electrical breakdown experiments of CO$_2$ and CO$_2$-O$_2$ (80-20)% for DC and impulse waveforms. In the latter sub-section, the results are discussed. These experiments were performed with the point-plane electrode arrangement as shown in Figure 3b.

#### 3.3.1 RESULTS

Figure 10 and Figure 11 show the breakdown voltages under DC and impulse waveforms, respectively. For the DC experiments with point-plane electrode only up to 20 shots were performed for every measurement point. In Figure 10, the breakdown strength of pure CO$_2$ stressed with negative polarity DC field increases linearly following about $11.5 \frac{kV}{cm.bar}$ up to 0.5 MPa. However, for positive polarity the exact trend is unclear due to the higher scatter at 0.4 MPa (small sample size). For CO$_2$-O$_2$ (80-20)% mixtures, the breakdown strength is marginally enhanced for negative polarity DC field and vice versa for positive DC field when compared to pure CO$_2$. The saturation seen at positive polarity is attributed to streamer to leader transition at pressures above 0.1 MPa as described in [7].

![Figure 8](image-url)  
**Figure 8.** AC breakdown strength in CO$_2$ and CO$_2$-O$_2$ Rod-plane geometry was used (Figure 3a) with a gap distance of 30 mm. An (~6%) increase in breakdown strength is observed under CO$_2$-O$_2$ (80-20)% mixture.

BD ratio is the ratio of breakdown strength of CO$_2$-O$_2$ to that of pure CO$_2$.

A systematic experimental study to find the electric strength of CO$_2$-O$_2$ binary mixtures with O$_2$ content of (0-30)% was performed to find the optimal mixture under impulse waveform. The experiments were performed in the pressure range of 0.1-0.3 and 0.5 MPa (only negative). Furthermore, the electric strength of CO$_2$-O$_2$ (80-20)% mixture in AC field for non-homogeneous fields was measured from 0.1-0.5 MPa.

It is seen in Figure 8 that by addition of 20% oxygen in CO$_2$, the median AC breakdown strength increases by approximately 5 kV at all the pressures. The increase in breakdown strength is about 9% at 0.1 MPa, 4.5-7% at 2, 3 and 0.4 MPa and 2.4% at 0.5 MPa as compared to pure CO$_2$.

![Figure 9](image-url)  
**Figure 9.** Breakdown in CO$_2$-O$_2$ mixtures for impulses (a) positive polarity and (b) negative polarity. The error bars represent the maximum withstand and minimum breakdown voltages.

![Figure 10](image-url)  
**Figure 10.** Breakdown voltage of CO$_2$ and CO$_2$-O$_2$ (80-20)% in DC for strongly non-homogeneous fields (point-plane electrode - Figure 3b). The gap distance was 15 mm.
Figure 11. The impulse breakdown voltage of CO$_2$ and CO$_2$-O$_2$ (80-20)% mixture for strongly non-homogeneous fields (point-plane electrode Figure 3b). The gap distance was 15 mm.

For impulse waveform (Figure 11), the difference between positive and negative breakdown strength is much larger and is interesting to note that the negative breakdown strength of CO$_2$ is significantly higher than positive impulse, which is the field required for streamer propagation and spark transition. Furthermore, addition of 20% oxygen to CO$_2$ increases the breakdown strength under negative polarity significantly, while the positive breakdown voltage is increased only marginally. The polarity effect is opposite to that seen in weakly non-homogeneous field. This was also reported by Wada et al. [8] at 0.7 MPa. The positive DC breakdown voltage at 0.5 MPa is slightly higher than that for impulse breakdown, which is attributed to differences in the needle tip diameters used in the experiments.

3.3.2 DISCUSSION

The field required for breakdown in negative impulse is about 14 kV/cm bar, which is higher than 11.5 kV/cm bar required for DC breakdown, due to the shorter timescale.

For positive impulse, the breakdown has a small linear increase in the 40-60 kV range with increasing pressure. The differences in breakdown voltage due to polarity in strongly non-homogeneous fields (point-plane) is similar to that observed in air [21]. Several mechanisms could be responsible for this behaviour:

- **Streamer to leader transition** in CO$_2$ above 0.1 MPa [7]: when the needle is stressed with positive polarity, leaders were observed with optical diagnostics. Thus, requiring a significantly lower breakdown field. However, for negative polarity, the breakdown mechanism is streamer breakdown and needs the streamer propagation field of $\sim 11$ kV/cm bar.

- **Corona stabilization (effect of space charge)** [13]: It suggests that when the needle is energized with the negative polarity field, a cloud of positive ions near the tip shields the discharge, hence requiring a high breakdown voltage. However, when positive polarity is applied, positive ions are pushed into the gap, enhancing the field in the gap and leading to a breakdown.

Figure 12. Total time lag to breakdown observed in strongly non-homogeneous fields (point-plane) for (a) positive and (b) negative impulse. In pure CO$_2$ breakdown for positive polarity pulses is around the peak of the pulse, but for negative polarity late and clustered breakdown ($>20$ µs) is observed.

It is possible that these phenomena are interrelated. Figure 12 shows the time lag to breakdown for both positive and negative polarity impulse in CO$_2$ and CO$_2$-O$_2$. It can be seen in Figure 12a, that all breakdowns occur before the peak of pulse for positive polarity, with no scatter, due to the strong field enhancement at the tip. However, the late and clustered breakdown in CO$_2$ negative polarity impulse, (Figure 12b) indicates that a time period in the order of 20 µs is needed for breakdown, close to the 50% breakdown value. To check if the time lags were caused by the lack of starting electrons in CO$_2$, experiments were performed at 0.3 MPa by irradiating the gap with UV-C (254 nm) light. The time lag to breakdown for negative polarity impulse is shown in Figure 13. It is seen that the time lag to breakdown is still high even with UV-C irradiation. Therefore, as expected, lack of starting electrons in negative polarity impulse is not a cause for the high time lags observed.

However, increasing the gap distance, leads to a quick breakdown, indicating that gap distance plays an important role in the discharge process. By eliminating the effect of starting electrons, the long time lag can be attributed to the time required for streamer propagation and spark transition or due to corona stabilization effect. The exact discharge mechanism for this time lag in pure CO$_2$ (Figure 12b) is unclear and further research with diagnostics such as pre-breakdown current measurements, along with a photomultiplier and high-speed imaging will be performed to understand the discharge process.
4 CONCLUSIONS

In this paper, the results of electrical breakdown in pure CO₂ and CO₂-O₂ mixtures in both weakly and strongly non-uniform electric fields at various pressures between 0.1 to 1 MPa are presented. The results of the experiments are compared with available literature. The results can be used as guidelines for designing HV equipment with CO₂ and CO₂-O₂ gas mixtures. Furthermore, these results will be used as a reference for further experiments to understand the discharge processes in CO₂ in detail. The results are summarized below:

- For weakly non-homogeneous fields (rod-plane), the first electron is less decisive for long duration waveforms (AC/DC), and breakdown is determined by streamer inception. For short duration waveforms (impulse) the availability of starting electrons is more significant. Thus, the breakdown strength in increasing order are AC/DC < negative impulse < positive impulse. For CO₂-O₂ mixtures a 6% increase in the breakdown strength was observed when applying AC waveform. However, for impulse no clear trends are seen in 10-30% oxygen admixtures.

- For strongly non-homogeneous fields (point-plane), the breakdown strength varies significantly with polarity (positive polarity has a lower breakdown strength). This indicates that the breakdown mechanism differs for both polarities and positive breakdown is critical for HV constructions. For CO₂-O₂ (80-20)%, the negative breakdown strength is enhanced compared to pure CO₂. The clustered but long time lags (>20 µs) observed in point-plane electrode geometry in CO₂ for negative impulse needs to be studied as further work.

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REFERENCES