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BREAKDOWN IN CO_2/O_2 AND $CO_2/O_2/$ C_2F_4 MIXTURES AT ELEVATED TEMPERATURES IN THE RANGE 1000–4000 K

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Abstract. CO_2 is a promising gas for replacement of SF_6 in high voltage circuit breakers. The electric breakdown in CO_2 and mixtures with C_2F_4 from PTFE nozzles is, however, still not fully understood. To understand the electric breakdown in CO_2 and mixtures with C_2F_4 from PTFE nozzles fundamental parameters like the temperature and pressure dependence of critical electric fields are needed. Data on critical fields is usually available based on simulations only and experimental validation is lacking so far. Our present contribution aims to close this gap and presents experiments where the breakdown fields in uniform and weakly non-uniform electric fields are determined at various temperatures and pressures. The gas temperatures were estimated from measurements with pyrometers. The results are compared to theoretical predictions.

Keywords: electric breakdown, CO_2, C_2F_4, dielectric recovery.

1. Introduction

Circuit breakers (CB) are important components in electrical power transmission and distribution networks. In gas circuit breakers, as used in high voltage transmission, mostly SF_6 is used today. Due to the high global warming potential of SF_6, search for alternative gases is ongoing since more than two decades and has intensified in the last decade. The most suitable alternative gases are identified to be CO_2 or mixtures of CO_2 with strongly attaching fluorinated gases [1, 2]. Since CO_2 is the base gas for all these new solutions it is very important to understand its properties under conditions of switching and insulation sufficiently well. For the dielectric interruption after arcing the dielectric properties of the hot gases need to be known. In the present contribution we present some results, where we investigated the breakdown fields in hot CO_2 and mixtures with PTFE (C_2F_4) vapor from the nozzles in uniform electric fields. Usually the breakdown in uniform fields occurs at streamer inception which is fulfilled slightly above the critical electric field, i.e. the zero crossing of the effective ionization coefficient, if voltage application time is sufficiently long to allow for spark transition. Therefore, measurement of the breakdown field in uniform or close to uniform electric fields may give an approximation for the critical field. At elevated gas temperatures, where precise measurements of the effective ionization coefficient are nearly impossible, such measurements give useful data to validate theoretical data based on solution of the Boltzmann equation. Section 2 describes the experimental set-ups, section 3 gives results and discussions. Conclusions are given in section 4.

2. Experimental setup

For the experiments a similar set-up as described in [3] was used. The test vessel was filled with CO_2/O_2 (90/10% mixture, molar fractions given throughout the paper) at 1, 2 and 4 bar. An arc was ignited between two contacts in a steel tube and the resulting hot gas was exhausted through a hole into a free gas space. This is denoted as hot gas generator in the following, see figure 1. The arcing gap was 35 mm, the relative contact speed about $3\,\mathrm{m{\cdot}s^{-1}}$ and the diameter of the plug contact 17 mm. The 50 Hz test current was varied between 4 . . . 5 kA peak. Arcing times were in the range of 25 . . . 28 ms, typically. The electrode with the hole on top of the hot gas generator was on ground potential. The diameter of the plate electrode was 150 mm and the hole had a diameter of 28 mm. Above the ground plate a parallel plate of same diameter was positioned, where HV was applied. The electrode gap was 38 mm in set-up 1. In set-up 2 a mesh grid was introduced 18 mm above the ground plate and electrically connected to it, resulting in an electrode gap of 20 mm. The hot gas generator was used with and without PTFE tube (see figure 1), which allowed for having C_2F_4 vapor or not in the hot gas stream.

The electrode arrangement was placed into a commercial gas insulated switchgear (GIS) vessel with a flange, equipped with a quartz window, allowing for optical observation of the discharges by high speed camera (Vision Research, Phantom V7.3, exposure time 20 . . . 80 µs). This window was also used to measure the infrared light in the gap with a fast infrared two color pyrometer (Kleiber, custom made, 990–1040 nm and 1100–1800 nm) in combination with a single-color pyrometer (Kleiber 740-LO, 2000–2200 nm). The time resolution of these pyrometers was less than 100 µs. The spot size for the pyrometer focus was about 2 mm in diameter and was adjusted to the mid gap position. Since in CO_2 and with PTFE nozzles as well we observed soot particles, the pyrometers measure the temperature of the soot particles. Assuming that these soot particles are in thermal equilibrium with the gas allows deducing the gas temperature from the pyrometer measurement. The test voltage was produced by a pre-charged capacitor (LC-circuit), which was switched onto the test gap by a triggered spark gap through a bushing in the GIS vessel. The test voltage had a rise time of 30 µs and a peak of 100 . . . 250 kV, depending on fill pressure and was switched onto the test gap at various instants during or after the sinusoidal high current half wave. In this way the breakdown voltage at different temperatures could be determined.

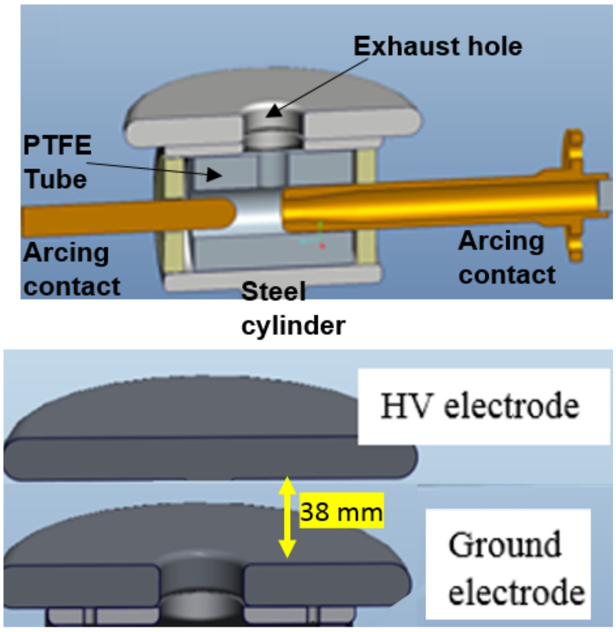

Figure 1. Hot gas generator and exhaust hole in ground electrode (top), electrode arrangement of set-up 1 (bottom).

3. Results

Typical hot gas distributions in the test gap and breakdown paths in both experiments are shown in figure 2. Usually in set-up 2, due to the mesh a more uniform light distribution of the hot gas was observed in the video frames, indicating possibly a more uniform temperature distribution. The breakdowns in set-up 1 happened sometimes at the hole edge. Set-up 2 was used for deducing the influence of the hole on the breakdown voltages.

From the pyrometer signals the temperature was deduced under assumption of same emissivity in all three bands. The resulting dependencies of breakdown voltages on temperatures for CO_2/O_2 and $CO_2/O_2/C_2F_4$ mixtures are shown in figure 3 and figure 4, respectively. The error bars show the uncertainties of the temperature evaluations. The figures show also predictions based on the critical electric field in hot CO_2/O_2 and $CO_2/O_2/C_2F_4$ mixtures. These predictions were obtained with an in-house code calculating the LTE particle composition and using Bolsig+ [4] for the electron energy distribution function with the cross sections retrieved from LXCAT [5].

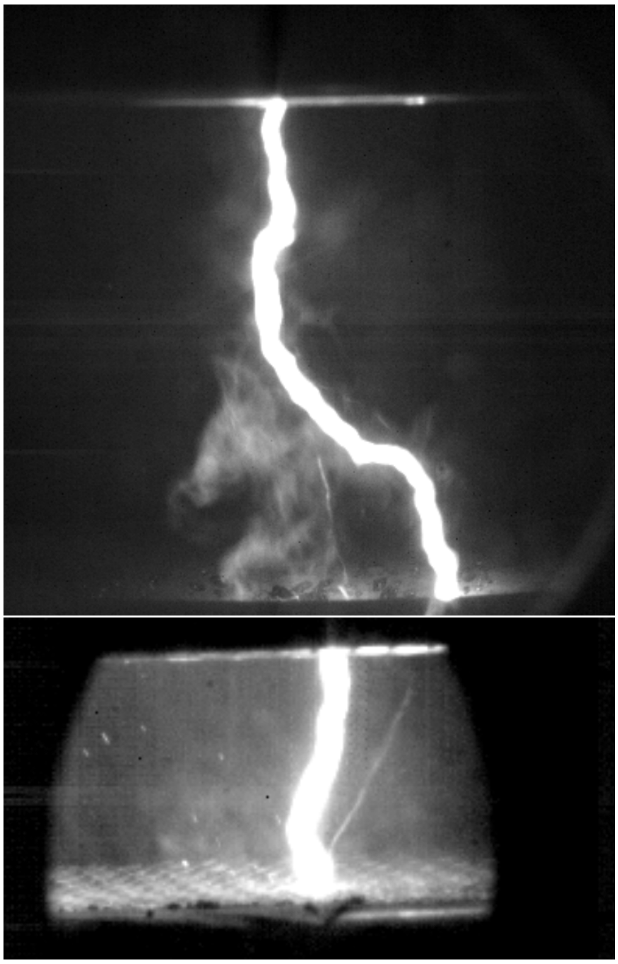

Figure 2. Breakdowns at 1 bar in set-up 1 (top) and set-up 2 (bottom).

The figures show that the experimental values exceed the predictions. This discrepancy can be partially understood by the higher field needed for streamer inception. This is shown for set-up 1 at 1 bar by the green curve. Additionally, the formative time lag plays a role, i.e. the time for streamer to spark transition, leading to higher breakdown voltages than only the critical field. Note that a formative time lag of a few microseconds translates into a voltage of several kV at the given steepness of the TRV (e.g. about 3 kV/µs at 1 bar). There are also variations in the temperature distributions which will lead to variations of breakdown voltages. Taking this into account, a reasonable agreement between calculated voltages from the critical fields and measured breakdown voltages can be stated, especially for the predicted trends of

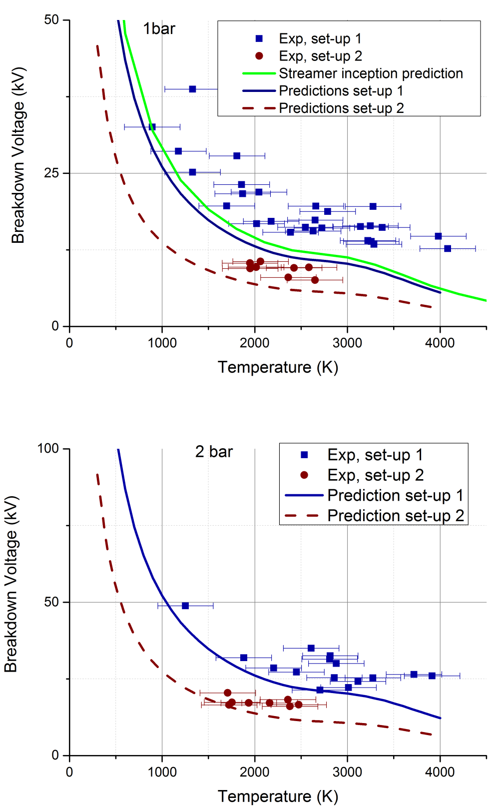

Figure 3. Breakdown voltages in CO_2/O_2 mixture vs temperature at 1 and 2 bar.

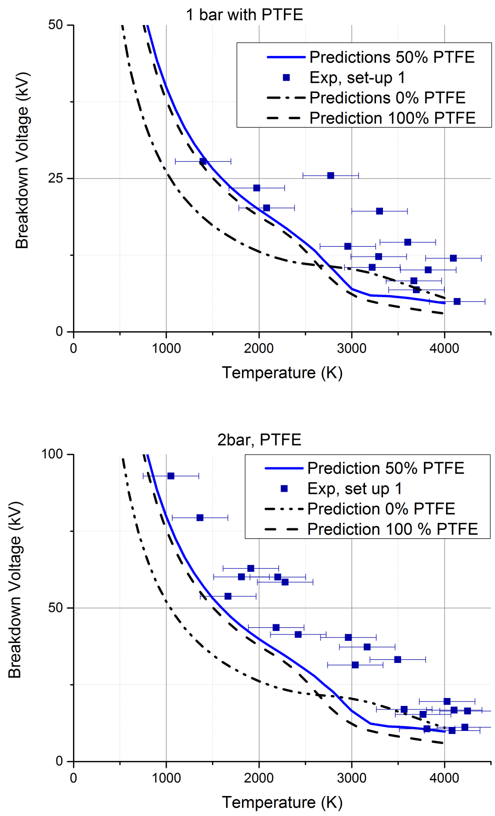

Figure 4. Breakdown voltages in $CO_2/O_2/\ C_2F_4$ mixture vs temperature at 1 and 2 bar.

the temperature dependencies. Only at higher temperatures, above 3000 K and CO_2/O_2 mixtures in the measurements there is less decrease of the breakdown voltage with increasing temperature compared to the predictions in figure 3. Comparing the breakdown voltages for set-up 1 and 2 we note that they scale with the gap distance, i.e. breakdown fields in both set-ups are the same. This indicates that influences due to field enhancement at the exhaust hole and temperature variations in both set-ups are within the uncertainties. For $CO_2/O_2/C_2F_4$ mixtures in figure 4 the C_2F_4 content was not determined. Therefore, the predictions are shown for various C_2F_4 contents (0, 50 and 100%). A reasonable agreement is seen with 50% curve (blue). Since the difference between 50% and 100% content is small, we can deduce that the PTFE content in the tests was probably about 50% or higher. This seems to be plausible since the arc is burning in PTFE vapor in the hot gas generator, i.e. there should be a large C_2F_4 content. Interestingly the agreement for the C_2F_4 mixtures is also satisfactory in the range above 3000 K. A similar agreement is seen at 4 bar for CO_2/O_2 and $CO_2/O_2/\ C_2F_4$ mixtures (not shown here).

The calculated critical electric fields can be plotted in particle density reduced form. This is shown in figure 5. These values can be compared to literature values, indicated by the symbols [6, 7]. A reasonable agreement of our calculations with the literature data is seen. Note that the literature values are for pure CO_2. For CO_2/O_2 mixture the critical fields are slightly higher than those for CO_2 below 3000 K, this was also observed in [7]. At 1 bar and temperatures above 3000 K we see a discrepancy between our predictions and those from literature. This needs further investigations. For C_2F_4 mixtures significantly higher critical fields can be seen below 2500 K compared to CO_2 and CO_2/O_2 mixtures.

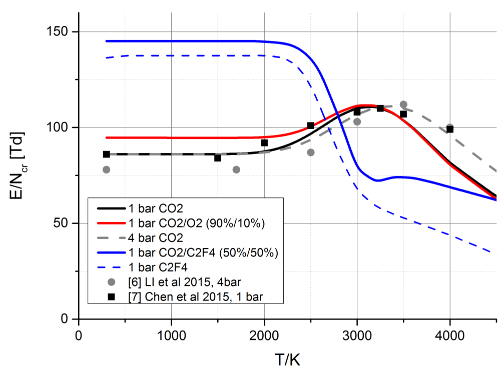

Figure 5. Predicted particle density reduced critical fields normalized to standard conditions of 300 K and 1 bar for CO_2/O_2, CO_2 and $CO_2/O_2/\ C_2F_4$ mixtures. Literature values for CO_2 are given by the symbols.

4. Conclusions

The breakdown in uniform electric fields in CO_2 at temperatures in the range 1000 . . . 4000 K is presented. Breakdown under such conditions was not experimentally investigated so far to our knowledge. The measurements can be compared to predictions of the critical field, which are a lower limit for the breakdown in uniform gaps. A reasonable agreement with the measurements can be seen when considering streamer inception and possible formative time lags. By this we validate, within the given uncertainties, not only our predictions but also those from literature.

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