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ELECTRIC BREAKDOWN IN A CO_2/O_2 GAS MIXTURE IN WEAKLY AND STRONGLY NON-UNIFORM ELECTRIC FIELD DISTRIBUTIONS AT TEMPERATURES OF 300–4000 K

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Abstract. Gas breakdown in weakly and strongly non-uniform electric fields at elevated temperatures, which can occur in gas circuit breakers after current interruption, is decisive for the performance of such devices. In a previous contribution [1], breakdown under such conditions was examined for the case of nearly uniform electric field distribution in a test setup. Results of an investigation of weakly to strongly uniform electric field distributions in axial and transverse gas flow will be shown in the present contribution. The pressure was typically in the range of 0.1 MPa to 0.4 MPa and temperatures were in the range of 300 K to 4000 K. The conditions for breakdown and their dependence on temperature and pressure will be discussed.

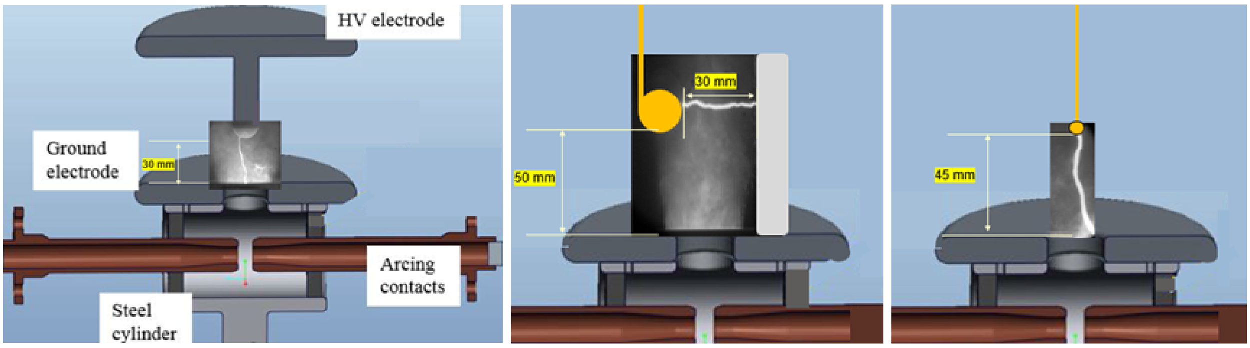
Keywords: SF_6 alternatives, Circuit breaker, CO_2, Electric Breakdown.

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 grids, SF_6 is the main gas used today. Due to the high global warming potential of SF_6, alternatives to SF_6 have been investigated over the last two decades and are available as products [2]. The most suitable alternative gases for live-tank circuit breakers, where the size of the circuit breaker is determined by the dielectric strength of the ambient air, are mixtures of CO_2/O_2. For metal-enclosed circuit breakers, where the size is defined by the properties of the insulating gas with which they are filled, strongly attaching fluorinated gases like C4-FN (C_4F_7N) need to be added to the mixture to ensure high dielectric strength and the same compact size as SF_6 equipment. To determine the dielectric interruption performance of switchgear after arcing, the dielectric properties of the hot gas remaining between the arcing contacts need to be known. In this contribution, we present results from a study where we investigated the breakdown voltages and fields in hot CO_2/O_2 mixtures for non-uniform electric fields. This study is an extension of a previous activity that investigated uniform electric fields, which allowed us to validate calculations of the critical electric field in such gas mixtures at elevated temperatures and in a pressure range of practical interest. Usually, breakdown in uniform and weakly non-uniform fields coincides with streamer inception at surface roughness of the electrodes. This behavior might be different in high temperature gases of a few 1000 K (as they occur after current interruption during the dielectric recovery phase). The results obtained for non-uniform fields, therefore, allow us to test hypotheses regarding the breakdown process under such conditions. Section 2 describes the experimental setups; Section 3 gives results and discussions. Conclusions are given in Section 4.

2. Experimental Setup

The setup described in [1] was used to perform the experiments; see Figure 1. The test vessel was filled with CO_2/O_2 (90/10% mixture, molar fractions given throughout the paper) at 0.1, 0.2 and 0.4 MPa. An arc was ignited between two contacts inside a steel tube, denoted as "hot gas generator" in the following; and the hot gas was exhausted through a hole into a larger volume above. The possible contribution of metal vapor to the hot gas flow was assumed to be negligible due to the relatively small currents. This was confirmed in our previous investigation where breakdown fields in uniform gaps agreed well with the critical electric field of the pure gas. The arcing gap was 35 mm; the relative contact opening speed was about $3\,\mathrm{m\,s^{-1}}$. The 50 Hz test current was varied between 4 kA to 5 kA peak. Arcing times were typically in the range of 25 ms to 28 ms. The electrode with the hole in it, which allows gas from the hot gas generator to pass through, was on ground potential. The diameter of this plate electrode was 150 mm and the hole had a diameter of 28 mm. Above the grounded plate different electrode configurations were placed. In contrast to the setup discussed in our previous paper, the electrode setups yielded weakly and strongly non-uniform electric fields. Three different setups were tested. For setups 1 and 3 the hot gas flow was in the axial direction with respect to the hole in the plate electrode. This may have led to temperature gradients that increased the uncertainties in the determination of the temperature distribution in the gap. Also, the hole in the bottom plate possibly



(a) . Setup 1 *(b) . Setup 2* *(c) . Setup 3*

Figure 1. Hot gas generator and exhaust hole in ground electrode (left), electrode arrangement of weakly non-uniform field setup 1 / setup 2 with $FE = E_{max} \cdot D = 3.5/3.66$; and strongly non-uniform field setup 3 with $FE = 11$. The vertical plate in setup 2 is on ground potential. The plug electrode in setup 1 had a diameter of 17 mm. The diameter of the sphere electrodes in setup 2 and setup 3 were 9.5 mm and 4 mm , respectively. Typical breakdown images are shown in the sketches of the setups.

slightly influenced the field distribution, as discussed in [1]. To reduce these uncertainties, a transverse flow geometry was realized in setup 2, with a similar field enhancement at the sphere. It was assumed that in this configuration the temperature distribution in the decisive region was more uniform. Note, that some temperature gradients in the vicinity of the metal electrodes cannot be avoided, but are estimated to have no significant influence on the results. In setup 3 a smaller sphere in an axial flow was used, leading to strongly non-uniform field in the gap.

The electrode arrangement was placed in a commercial gas-insulated switchgear (GIS) vessel with a flange equipped with quartz windows, allowing for optical observation of the discharges with a high-speed camera (Vision Research, Phantom V7.3, exposure time 20 µs to 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, which was a reasonable approximation of the average temperature in the gap, as described in our previous publication [1]. Variation of the spot position in the gap did not significantly alter the results. As explained in [1], the pyrometers measure the temperature of soot particles forming in the CO_2/O_2 gas mixture. Assuming that these soot particles are in thermal equilibrium with the gas allows deduction of the gas temperature from the pyrometer measurement. The test voltage was produced by a pre-charged capacitor (LC-circuit) and switched onto the test gap by a triggered spark gap through a bushing in the GIS vessel. Positive and negative polarity was tested. The test voltage had a rise time of 30 µs and a peak of voltage of 100 kV to 250 kV 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. In one test a slower rise time with about 200 µs time to peak was used, denoted as "slow TRV" in the following.

3. Results

Figures 2, 3, and 4 show the dependence of the breakdown voltage in setup 1, setup 2 and setup 3, respectively vs temperature in the middle of the gap. Before the tests, the temperature at various positions along the axis of symmetry was checked and was found not to be significantly different from the mid-gap temperature, i.e., the mid-gap temperature is a good approximation for the average temperature in the gap within the error bars. The experimental data points are compared to calculations of the breakdown voltage for the given electrode arrangement, temperatures T, and pressures p. These calculations are: (1) streamer inception criterion ("Inc"), (2) propagation at critical field ("Propagation"), and (3) the upper bound on the breakdown voltage given by the voltage at which the electric field everywhere in the gap is calculated to be at or above the critical field ("Max BD"). Streamer inception ("Inc") was calculated for the capacitive electric field distribution using the effective ionization coefficient for the CO_2/O_2 mixture for a range of temperatures and pressures. This coefficient was obtained, as in [1], using an in-house code that calculates the LTE particle composition and Bolsig+ [3] to determine the electron energy distribution function based on cross sections retrieved from LXCAT [4]. The critical electric fields E_{cr} were deduced from the zero crossing of the effective ionization coefficient. The streamer ionization integral parameter was chosen to be K=13. The voltage at which propagation at the critical field occurs (labeled "Propagation" in the plots) through the gap of length D (along the axis of symmetry z) for a given temperature and pressure distribution was calculated using $U_{prop} = \int_0^D E_{cr}(T,p) \cdot dz$. For

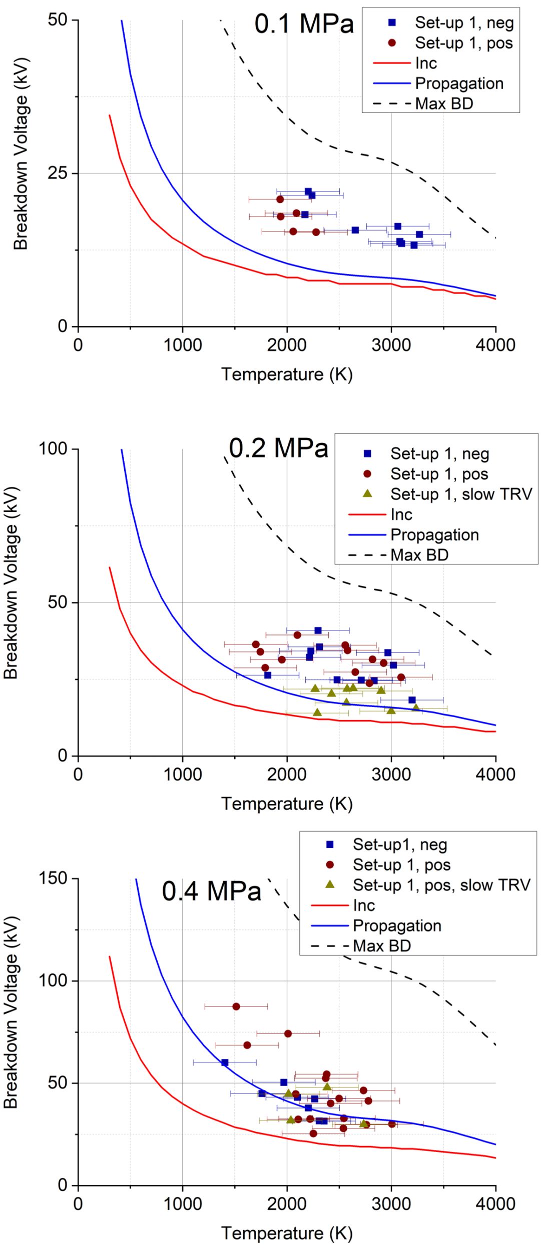


Figure 2. Breakdown voltage vs temperature for setup 1. The theoretical streamer inception (Inc) voltage and propagation at the critical field are both shown for comparison. The "Max BD" denotes voltages at which the field across the whole gap is at or above the critical electric field. The horizontal error bars give the estimated uncertainties of the temperature determination.

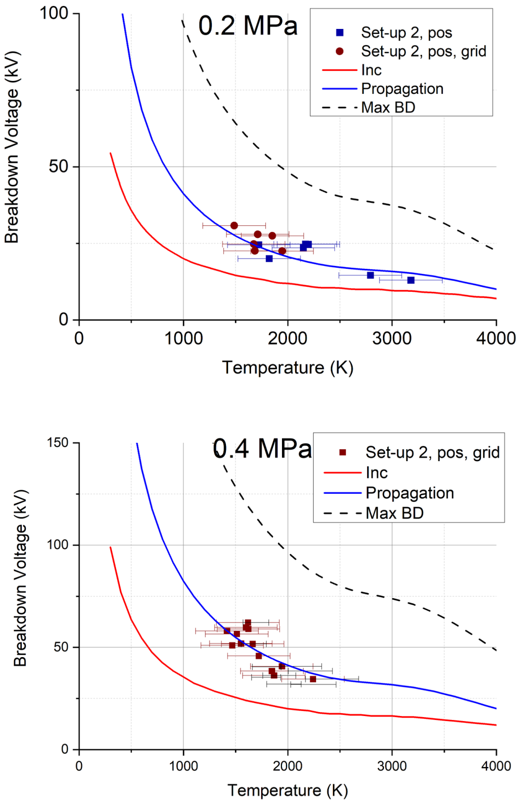


Figure 3. Breakdown voltage vs temperature for setup 2. The theoretical streamer inception (Inc) voltage and propagation at the critical field is shown for comparison. The "Max BD" denotes voltages at which the field across the whole gap is at or above the critical electric field. The horizontal error bars give the estimated uncertainties of the temperature determination.

a constant average temperature T_{av} this reduces to $U_{\text{prop}} = E_{\text{cr}}(T_{\text{av}}, p) \cdot D$. Note that this very simple criterion does not depend on the field distribution in the gap but only on pressure, temperature, and gap length. The "Max BD" criterion is described by $U_{MaxBD} = E_{cr}(p, T_{av})/\min(e(z))$. Breakdown is assumed to take place along the axis of symmetry z; $e(z)$ denotes the voltage reduced capacitive electric field distribution; and p and T_{av} represent the pressure and the average temperature.

The results from the various experiments show that for all setups the breakdown voltage decreases with increasing temperature and increases with increasing pressure as can be expected from the dependencies of the critical field shown in [1]. For setup 1 (Figure 2) the best agreement of the experimental points is seen for the model that assumes propagation at the critical field; see blue curve in the figures. This indicates that streamer inception (red curves) is not sufficient for breakdown but that the discharge propagates through the gap only at the critical field, which can lead to breakdown. This behavior is not significantly different for the two polarities. At 0.2 MPa slightly lower breakdown voltages might be seen for the slow TRV, which would fit with the expectation that for slower TRV rise time lags for inception and propagation would play less of a role. For the few datapoints at 0.4 MPa this is, however, not observed. High breakdown values, well above the propagation criterion, e.g., at 0.1 MPa, might also be produced by systematic uncertainties of the temperature evaluation, which is based on the mid-gap temperature in a single spot. There might be a tendency for the breakdown voltages to be closer

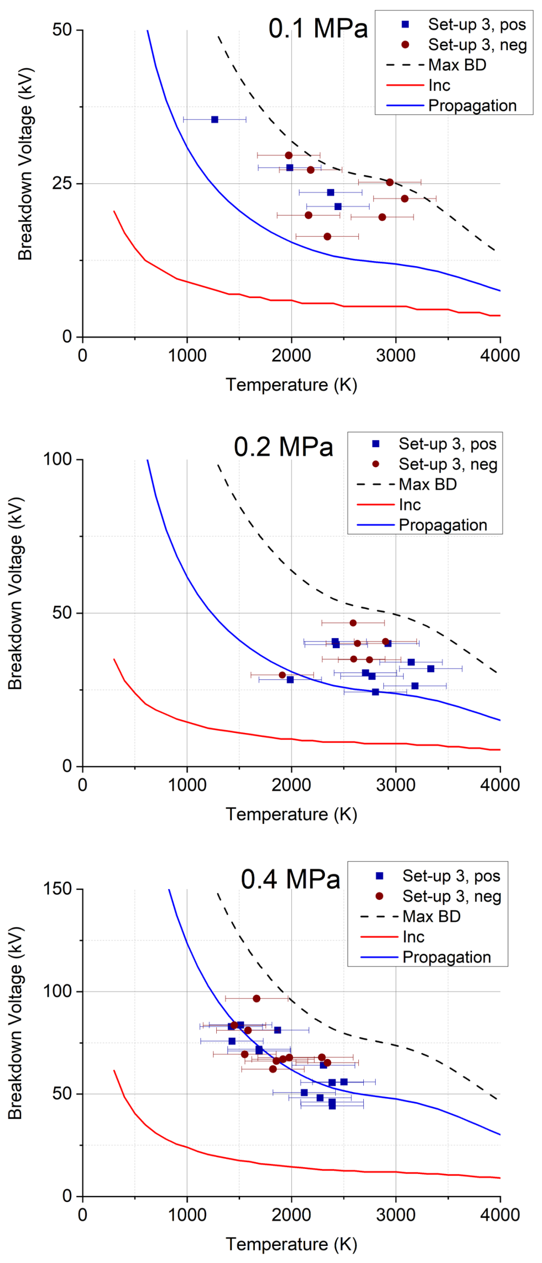


Figure 4. Breakdown voltage vs temperature for setup 3. The theoretical streamer inception (Inc) voltage and propagation at the critical field is shown for comparison. The "Max BD" denotes voltages at which the field across the whole gap is at or above the critical electric field. The horizontal error bars give the estimated uncertainties of the temperature determination.

to the propagation criterion at higher pressures. The "max BD" criterion, where the field is at or above the critical field everywhere in the gap is much higher than the other criteria.

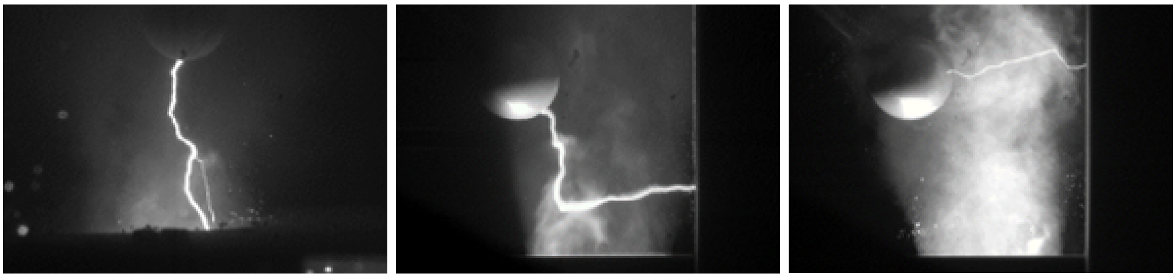
For setup 2 (Figure 3) we see similar breakdown voltages as for setup 1. This can be expected since the field distribution in the gap is nearly identical. It shows that the mid-gap temperature measurement yields a good approximation for the average temperature in the gap for both setups. However, a reduced scatter can be seen with setup 2, indicating less temperature variations in the gap compared to setup 1. Possibly, the temperature distribution in the gap in setup 2 is more uniform and also more reproducible. In one experiment with setup 2, a mesh grid was inserted at the exhaust hole of the hot gas generator. This lowered the temperature efficiently, as can be seen in Figure 3.

The results for the strongly non-uniform fields are shown in Figure 4. Streamer inception is predicted at much lower voltages compared to the propagation criterion, which again best describes the experimental data. Compared to setup 1 and setup 2, the measured breakdown voltages are higher with setup 3, which is most likely due to the larger gap. This is reflected in the agreement with the propagation criterion, which scales with the gap length for the same average temperature. The scatter of the breakdown voltages is similar to that of setup 1 and again at the higher pressure of 0.4 MPa the results are closer to the propagation criterion compared to the results at 0.1 MPa and at 0.2 MPa. The "max BD" criterion is the upper limit for those cases. Most breakdowns in all the experiments occurred on a relatively straight path, as shown in the examples of Figure 1. In a few cases, however, different breakdown paths occurred; see Figure 5. Pronounced deviations from straight propagation can be seen. In these cases, the hot gas distribution was non-uniform and obviously influenced the propagation path. All these events were included in the data analysis, i.e. were within the variation of the data points.

Images of partial discharges in the three setups are shown in Figure 6. These images show a wiggly propagation (left image); branching (center image) and discharges starting from a hot gas cloud without leading to breakdown (right image). The light intensity of these discharges indicates some channel heating, as would be expected in a leader channel [5]. The wiggly propagation path indicates that propagation under these conditions does not necessarily occur on a straight path but follow the path of highest temperature, i.e., lowest critical field, as could be interpreted also from the breakdown paths in Figure 5.

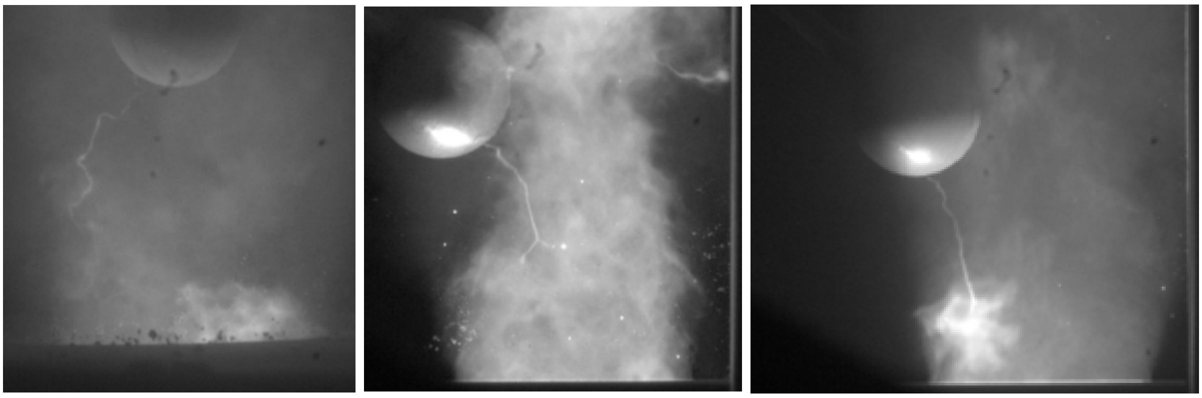
4. Conclusions

The breakdown voltages in weakly and strongly non-uniform electric fields in a CO_2/O_2 (90%/10%) mixture for temperatures in the range 1000 K to 4000 K are presented. Hot gas was produced by an arc in a hot gas generator and exhausted into the test gap. Three different test setups were used with both axial and transverse gas flows in relation to the axis of symmetry. This study is an extension of a previous study of uniform electric fields [1]. The measurements are compared to predictions of streamer inception, propagation at the critical field, and overcritical gap models. A reasonable agreement with the measurements can be seen for the propagation criterion for



(a) . Setup 1: 33 kV, 0.4 MPa *(b) . Setup 2:* 24 kV, 0.2 MPa *(c) . Setup 2:* 14 kV, 0.2 MPa

Figure 5. Breakdown path images.



(a) . Setup 1: 30 kV, 0.4 MPa *(b) . Setup 2:* 14 kV, 0.2 MPa *(c) . Setup 2:* 25 kV, 0.2 MPa

Figure 6. Partial discharge images.

all cases under the investigated conditions. Images give further insight into how the hot gas distribution influences propagation. Observation of partial discharges indicates that propagation occurs via leader propagation.

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