# Characterizing streamer discharges in $CO_2$ and Air

B. Bagheri [1], J. Teunissen[1,2] and U. Ebert[1,3]

[1]*Centrum Wiskunde & Informatica, Amsterdam, the Netherlands*
[2] *Centre for Mathematical Plasma-Astrophysics, KU Leuven, Belgium*
[3]*Department of Applied Physics, Eindhoven University of Technology, the Netherlands*

**Abstract:** Understanding breakdown dynamics in $CO_2$ is of great interests for both high-voltage technology and lightning on Venus. $CO_2$ is a promising gas for substituting $SF_6$ in high-voltage switchgear due to its lower global warming potential. Streamers play a decisive role in gas breakdown. Therefore, understanding streamer properties such as inception and propagation is of great importance. In this work, we investigate streamer parameters such as velocity, radius, and stability-field in $CO_2$ and air for positive and negative polarities.

**Keywords:** streamer parameters, stability field, negative and positive polarities.

## 1. Introduction

Sparks, arcs and lightning are well-known examples of electric gas discharges that not only occur in nature but also have numerous technical applications [1-4]. In electric power transmission and distribution systems, pressurized gas is widely used for insulation and current interruption purposes [5]. $SF_6$ is the most efficient gas for this purpose. However, it is a very strong greenhouse gas [6]. There is plenty of ongoing research for an alternative gas. Several investigations have revealed that $CO_2$ is a promising substitute for $SF_6$ in high-voltage switchgear. Recently, a commercial breaker using $CO_2$ was introduced to the market. However, little knowledge is available about the electric breakdown mechanism in $CO_2$. The typical pressure range of such kind of applications is 1-10 bar [4]. Furthermore, investigation of electric breakdown in $CO_2$ is relevant for understanding lightning on Venus with an atmosphere of $CO_2$-$N_2$ $(96.5\% - 3.5\%)$. Even though electromagnetic remote sensing indicates lightning on Venus at a similar frequency as on earth, no optical signature of lighting activity on Venus has been reported [7].

There have been lots of studies on the dynamics of electric breakdown in ambient air under common conditions, however less knowledge is available when gas composition, pressure or temperature change. It is typically assumed that electric breakdown evolves from initial seed electron avalanches and creation of space charge dominated streamer phase and then to a heat dominated phase. It is extremely important to understand which chemical reactions are responsible for each phase of the discharge. Streamers are decisive for breakdown in gases and hence understanding streamer properties such as inception and propagation is essential. Streamers emerge in two polarities, positive and negative, propagating with or against the electron drift. Positive streamers emerge and propagate easier than negative ones and they need a source of free electrons in front of their heads for their propagation [8].

One of the important parameters is the so called "streamer stability field". The typical value of pressure-reduced stability field is about 4-5.5 $\mathrm{V(m\,Pa)^{-1}}$ for positive streamers and 12.5 $\mathrm{V(m\,Pa)^{-1}}$ for negative streamer in atmospheric air [4]. Experimental measurements of [4] revealed that the pressure-reduced stability field for negative streamers in $CO_2$ is lower than for positive polarity. This is opposite to air. In the present contribution, we investigate streamer parameters including stability-field for positive and negative streamers in dry air ($N_2$-$O_2$), $CO_2$, and their mixtures. Characterization of these parameters allows a better understanding of insulation performance of $CO_2$ breakers. It is also valuable for the plasma-chemical applications in $CO_2$ containing gases [9].

## 2. Methodology

Here we employ a drift-diffusion-reaction type fluid model. The electron density ($n_e$) and positive ion density ($n_i$) evolve in time as

$$\partial_t n_e = \nabla.\left(n_e \mu_e \vec{E} + D_e \nabla n_e\right) + S_i + S_{ph},$$

$$\partial_t n_e = S_i + S_{ph},$$

in which $D_e$ is the electron diffusion coefficient, $\mu_e$ is the electron mobility, $\vec{E}$ is the electric field. $S_i$ is the ionization source term

$$S_i = \bar{\alpha}\mu_e\left|\vec{E}\right|n_e,$$

where $\bar{\alpha} = (\alpha - \eta)$ is the effective ionization coefficient. $\alpha$ and $\eta$ are ionization and attachment coefficients, respectively. $S_{ph}$ is the non-local photoionization source term. We ignore the transport of ions on the short time scale of streamer propagation. The local field approximation is used for the transport coefficients.

The electric field is calculated in the electrostatic approximation

$$\vec{E} = -\nabla\varphi,$$
$$\nabla^2\varphi = -\frac{e(n_i - n_e)}{\varepsilon_0},$$

where $\varphi$ is the electric potential, $\varepsilon_0$ the vacuum permittivity, and $e$ the electron charge.
The fluid model described above is implemented in Afivo-streamer code [10-12], which is based on geometric multigrid methods to solve the Poisson's equation, octree adaptive mesh refinement and OpenMP parallelism. We perform fully 3D simulations as well as 2D cylindrically symmetric simulations using the Afivo-streamer code.

One important ingredient specially for positive streamers is the photoionization source term. Positive streamers require a source of free electrons in front of their heads. Photoionization is one source for these electrons. In $N_2$-$O_2$ mixtures, nitrogen molecules are the source of the ionizing radiation which can be absorbed by oxygen molecules. This leads to the ionization of these oxygen molecules and generation of free electrons. The photoionization source term is given by

$$S_{ph} = \int d^3r' \frac{I(r')f(|r-r'|)}{4\pi|r-r'|^2}.$$

$I(r)$ is the source of ionizing photons, $f(r)$ the absorption function, and $4\pi|r-r'|^2$ a geometric factor. $f(r)$ gives the probability density of a photon being absorbed at a distance $r$.

According to Zheleznyak's photoionization model [14] for $N_2$-$O_2$ mixtures, the absorption function is

$$f(r) = \frac{\exp\left(-\mathrm{X}_{\min} p_{O_2} r\right) - \exp\left(-\mathrm{X}_{\max} p_{O_2} r\right)}{r\, ln\left(\frac{\mathrm{X}_{\max}}{\mathrm{X}_{\min}}\right)},$$

where $p_{O_2}$ is the partial pressure of oxygen, $\mathrm{X}_{\max} \approx 1.5 \times \frac{10^2}{\mathrm{mm\ bar}}$, and $\mathrm{X}_{\max} \approx \frac{2.6}{\mathrm{mm\ bar}}$. The photon source term is given by

$$I(r) = \frac{p_q}{(p+p_q)} \xi \alpha \mu_e |\vec{E}| n_e,$$

where $\xi$ is the proportionality factor, $\frac{p_q}{(p+p_q)}$ accounts for collisional quenching of excited nitrogen molecules, and $\alpha$ is the impact ionization coefficient. $p$ is the gas pressure and $p_q$ the quenching pressure. We use $p_q = 40$ mbar. In the present work, we employ Zheleznyak's photoionization model for simulation of streamers in $N_2$-$O_2$ mixtures, and we present a possible modification to the UV photon source term $I(r)$. We discuss how the results are affected by this modification.

Even though there have been lots of studies for photoionization in $N_2$-$O_2$ mixtures, the mechanism is not clearly understood in $CO_2$ [13-15]. Here, we also discuss photoionization in $CO_2$ and the corresponding reactions and species for creating possible ionizing radiations and their absorption.

## 3. Results

Figure 1 shows the electric field profile for axisymmetric simulation in dry air at 13 ns.
We present the results of streamer parameters (streamer velocity, radius, stability field) for positive and negative streamers in different mixtures of $CO_2$ - $N_2$ - $O_2$.

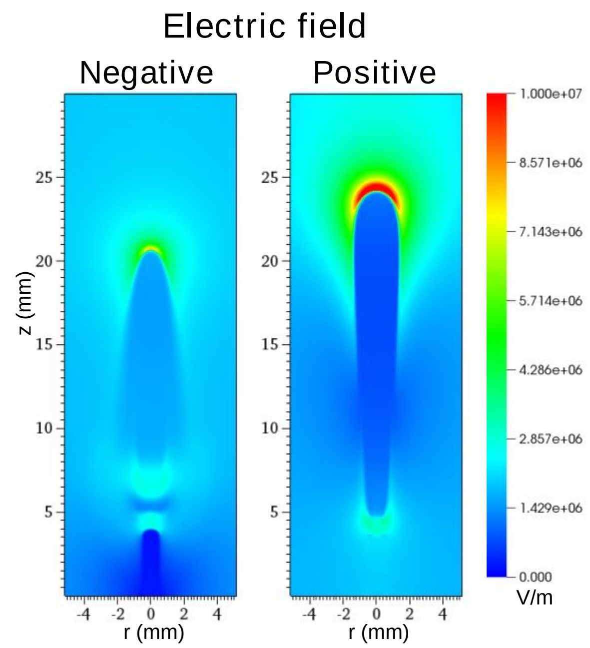


Figure 1. Electric field profile for axisymmetric simulation in dry air for negative and positive polarities. The width of the domain in the $r$-direction is 3 cm; only a part of it is shown here.


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