Simulation of positive and negative streamer in a CO2/O2 gas mixture

Hafiz Muhammad Tahir Nisar1, Muhammad Farasat Abbas1\* Guang Yu Sun2

1 High Voltage Lab, Department of Electrical Engineering Power, U.S.-Pakistan Centre for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology (NUST), H-12, Islamabad, 44000 Pakistan

2 Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

\*E-mail: [farasat.abbas@uspcase.nust.edu.pk](mailto:farasat.abbas@uspcase.nust.edu.pk)

Abstract

SF6 is commonly used as gaseous insulation media in high voltage equipment but it has high GWP and urgently needs to be replaced with ecofriendly alternatives. CO2 based mixtures have shown promising results as SF6 alternatives. Streamers belonging to the initial phase of electrical breakdown have become an important subject for the reliable design of high voltage equipment based on gaseous insulation. In this paper, positive and negative streamers in CO2/O2 mixtures are investigated using a 2D axisymmetric simulation model. Considering the low probability in gas mixtures with higher concentration of CO2, photoionization has been excluded andbackground ionization is used for the generation of free electrons along with Townsend ionization equation and the Gaussian approximation for the initial electron density distribution.

The influence of concentration ratio, pressure, electric field non-uniformity, and gap length on both positive and negative streamers is then investigated along with electron transport properties.

The results showed that with increasing the O2 content into CO2, electron density, electric field, streamer length, and velocity decreased/increased for positive streamer and what happened in the case of negative streamer??? Similarly, what was the impact of increasing the pressure, electrode radii, and gap length on positive and negative streamers???

The results showed that electron density, electric field and total ionization rate in negative streamer discharge is higher and concentrated as compared to positive streamer discharge. The electron density in positive and negative streamer increases by increasing the voltage and decreases with increase in the pressure, electrode radii and electrode distance. Similarly, the streamer propagation velocity in positive streamer is fast as compared with negative streamer. In positive streamer, the localized electric field is enhanced by the electron impact reaction and hence the streamer propagation velocity increases. From the graphical results, the electric field in negative streamer first increases and then decreases. The negative streamer propagates against the electric field. On the other hand, the positive streamer propagates in the direction of the electric field. Therefore, the electric field in positive streamer has the maximum peak during the propagation of the streamer discharge.

Keywords: We can write this on the end.

1. Introduction

Sulphur hexafluoride (SF6) is commonly utilized as a gas for quenching arcs during fault occurrences in various high-voltage devices like circuit breakers, gas-insulated switchgear (GIS), and gas-insulated lines (GIL), providing essential functions in high-voltage fault protection and insulation. However, its significant global warming potential (GWP) index classifies SF6 as one of the most potent gases ever generated [1]. The GWP index of SF6 is about 23,500 times higher than that of CO2 [2]. Therefore, it is important to replace the SF6 gas with a new eco-friendly gas or gas mixtures with properties comparable to SF6 [3]. CO2 plays an important role in switching performance and has a promising SF6 replacement capability either in pure form or mixed with other materials such as C4F7N, CF3I or C5F10O [4][5].

The literature has shown different authors have carried out streamer discharge experiments based on the CO2 mixed gases. Lin et al. performed the experiment on the positive streamer discharge under AC and DC composite voltage. The key characteristics of the positive streamer including streamer propagation, streamer velocity and luminous intensity have discussed in detail. The experiment results have proved that the positive streamer discharge characteristics under the AC and DC composite voltage are different from the pure DC voltage. The positive streamer discharge is dependent on the phase of the applied voltage [6]. Kumar et al. also performed the experiment on CO2/O2 under AC, DC and impulse applied voltage in a weak and strong non-uniform electric field at 0.1 to 1 MPa of the applied pressure. The results of this experiment have shown that in a weak non-uniform electric field, the breakdown electric field is followed by a constant ratio under AC and DC applied voltage. The positive impulse voltage has higher breakdown strength than AC and DC voltage. Similarly, the breakdown strength under negative impulse voltage is further higher than the positive impulse voltage in a non-uniform electric field [7]. Similarly, Huiskamp et al. worked on the effective streamer discharge propagation control with the help of nanosecond pulsed waveform generator. The results of the experiment have shown that streamer propagation can be controlled by controlling the stepped waveform but the pulse rise time has little effect on the streamer propagation. However, streamer velocity changes significantly by changing the rise and fall time pulsed waveform generator [8].

The streamer discharge simulation in CO2 mixture has also carried out by different authors. Bagheri et al. performed the simulation of positive streamer discharge in CO2 with and without air mixture. As the photoionization mechanism in CO2 has low probability, therefore background ionization mechanism has used for the study of the positive streamer [9]. The simulation results of this paper depicted that streamer propagation is less dependent on the level of the background ionization. The other factors like electric field, applied voltage, electron mobility (µ) and ionization coefficient (α) are strongly dependent on the streamer propagation. Furthermore, Li and other co-authors worked on the streamer discharge simulation in CO2 using particle-in-cell model. They proposed that photoionization in CO2 is much weaker when compared with air, because the probability of ionization photons in CO­2 is very low. The positive streamer can initiate and sustain with a small amount of photoionization but this requires a very high electric field around the streamer head. Hence the sustainability of positive streamer in CO2 depends on the electric filed value [10]. Similarly, Marskar performed the streamer discharge simulation in CO2 by using the 3D kinetic Monte Carlo model. The author concluded from the simulation results that electron attachment and photoionization both are required for the streamer to initiate and propagate. The electron attachment plays critical role in negative streamer whereas photoionization in positive streamer discharge. The author performed the computational analysis and concluded that positive streamer can propagate due to photoionization in CO2 based gas mixture[11]. CO2 is considered as the prominent alternative gas as from the above literature. As the photoionization in CO2 is weak, so the background ionization has selected as an alternative breakdown mechanism.

The main focus of this paper is to understand the positive and negative streamer discharge behavior under different parameters, such as time span, applied voltage, pressure, electrode radii, electrode distance and streamer velocity. The behavior of streamer formation in negative and positive streamer discharge has discussed in detail. This includes the influence of charged particles, including ions and electrons, and the streamer head formation during the propagation. The change of the streamer formation on the head is also analyzed and discussed in detail. (Rewrite)

The paper is distributed in three major sections. In the first section, the two-dimensional axis-symmetric model has been established in a plasma domain. In the second section, the streamer discharge formation in the CO2/O2 gas mixture, along with different parameters is discussed in detail. The third section is based on the conclusion of the whole paper. The main contribution of this work includes the detailed study of positive and negative streamer discharge under different influence conditions. The propagation of the streamer and the formation of localized ions ahead of the streamer head have been discussed in detail. The role of ionization energy in streamer formation and the influence of the molecular structure on the streamer velocity are also discussed in detail.

[12]. [13]. [14]. [15]. The study also revealed that the influence of streamer discharge on electron density during propagation is still missing in different literature. For the negative streamer discharge, electrons are abundant, and the streamer head is carried by electrons, while in positive streamer discharge, the streamer head is carried by positive ions [16-18].

In this work, first calculate the swarm parameters of CO2 and O2 by considering the Boltzmann two-term approximation equation. CO2/O2 mixtures are selected as the study object in this work [19]. The swarm parameters include electron mean energy, diffusion coefficient, electron mobility, reduced ionization and attachment coefficient and electron energy distribution function. The purpose of swarm parameters calculation is to understand the streamer initiation and propagation by relating the swarm parameters with streamer discharge initiation and propagation [5, 20].

3. 2D Axis-Symmetric Simulation Model

The simulation model of CO2/O2 is shown in figure 8 below. The simulation is carried out in a FEM (Finite Element Method) based software COMSOL Multiphysics. In figure 8 below, (**a**) is a rod electrode with a diameter of 2mm, (**b**) is the plane electrode and having length 4mm, and (**c**) is the boundary of the streamer discharge as well as for the CO2/O2 mixture with a length of 6mm. The distance between the rod to plane electrode is 4mm. The entire simulation model is covered with a free mesh triangular network. To obtain more accurate results, the mesh near the rod electrode is significantly increased [5]. Furthermore, for the initial density distribution, the Gaussian approximation has been used, as explained in the below section.

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Figure 1 Streamer discharge plasma model

The streamer discharge plasma model of CO2/O2 is based on various studies, including the distribution and the density of the different components in the CO2/O2 mixture. Different studies have shown the simulation-based fluid modeling of CO2 mixed with other gases (O2, N2, SF6), but few of them have studied the specific component produced in the discharge during the streamer initiation process [5]. This paper focused on the streamer discharge initiation and propagation by analyzing the various parameters and ionization reactions, including the source term equations and the analysis of the streamer discharge velocity in CO2/O2 mixture.

The simulation of streamer discharge through fluid modeling involves the utilization of several equations, including the fundamental drift-diffusion and Poisson equations. In fluid modeling, a popular formulation for simulating streamer discharge in a background gas relies on the drift-diffusion technique. This approach takes into account the variations in densities of both positive and negative ions. Consequently, it leads to the derivation of a partial differential equation (PDE), expressed as follows [21].

where *n*e ­­is the electron density (m-3), *µ*e is the mobility (m2/Vs), *D*is the diffusion coefficient (m2/s), **E** is theelectric field (V/m)**,** *R*eis therateof generation and loss processes (m-3s-1) and t stand for time.

The initiation of the streamer process in a background gas is usually represented by their respective rates as given in equation 2. The first electron loss rate is an electron impact ionization and the rate of loss process is given as [15].

where *α* (m-1) is the ionization coefficient.

Similarly, the rate for the attachment and detachment of electrons to the electronegative gas (O2, CO2, SF6, etc.) is represented by the following equations [15].

where *η* (m-1) is the attachment coefficient.

Equations (5-10) represents the generation and loss of ions and electrons in a background gas such as CO2/O2. To understand the variation in ions with respect to the time, the ion drift-diffusion is used as given below [21].

*wk* represents the mass faction of the specie *k*, *R­k* represents the rate expression of generation and *ρ* represents the density of the gas mixture.

For the streamer to initiate and develop, Poisson equation plays a critical role in determining the electric field distributions as a result of the space charge formation in the process of streamer development. The Poisson equation is represented by the following equation [5].

*εr* represents the relative permeability, *ε*0 is the absolute permeability, q is the elementary charge and ∇V represents the gradient of the electric potential.

## 3.1 Parameter settings

The rod electrode as shown in figure 8 is (a) and plane electrode is (b). The boundary conditions for the rod electrode is given by the equation.

Whereas the boundary condition for the plane electrode is given by the following equation.

### Insulation and zero charge boundary

For the insulation and zero charge boundary condition of CO2/O2 as shown in above figure 8, it is assumed that no charge on the boundary and zero electron flux is on the boundary. These two boundary conditions are described by the following equations [5].

## 3.2 Background equations and initial density distribution

The initial density distribution for electron positive and negative ions is based on the Gaussian distribution. The streamer propagates within the boundary of the simulation under the background gas mixture can be controlled by controlling the Gaussian distribution parameters. The equation 10 represents the Gaussian approximation for initial density distribution for electrons, positive and negative ions [14].

where r and z is the coordinates of streamer discharge along the x and y axis. r0 and z0 is the coordinates of the rod electrode. s0 is the radius of the initial distribution particles. The maximum initial electron density in the beginning is at the tip of the electrode and hence the propagation of streamer along the z axis will become easy.

For the secondary emission of electrons Townsend first ionization coefficient has used to determine the secondary electron emissions from the electron impact reaction. The Townsend first ionization coefficient is given below in equation 11 [22].

where A and B are the constants. P is the pressure in Torr and E is the electric field (V/m).

## 3.3 Initial conditions and reaction mechanism

For the simulation of streamer discharge in CO2/O2 mixture, the initial electron density value is selected based on the accurate simulation results. The initial value of electron density is 1×1022 (m-3). The initial ion density value (CO2+, O2+, O2- etc.) is taken as 1×1019 (m-3) .The initial value of electron and ion mobility is 1.2×105 (m2/V.s) and 1.3×102 (m2/V.s) respectively. The initial value of longitudinal and transverse electron diffusion is in between the range of 1800 and 2190 (m2/s). The initial electric potential is 0 V, and the initial electron energy is 3 eV respectively [5].

The reaction mechanism for the streamer discharge in CO2/O2 is presented in table 1 as shown below. These reactions are not only used for the electron transport properties with the help of Boltzmann's two-term approximation but also used in the streamer discharge development in CO2/O2 gas mixture. Reaction R1-R27 has been taken from the LXCat database [23]. In this paper, four different reactions – elastic, excitation, attachment and ionization – are used for the study of insulation properties of CO2 and O2 gas mixture. Reaction R2 is the elastic collision reaction of CO2. Reactions R13 and R27 are the ionization reactions of CO2 and O2. R1 and R26 are the attachment reactions of CO2 and O2. The rest of the reactions are the excitation reactions. In this paper, the main focus is to study the influence of electronegative gas and the corresponding reactions on the streamer formation in CO2/O2 gas mixture.

**Table 11.** Reaction mechanism and collision cross section

|  |  |  |  |
| --- | --- | --- | --- |
| **Reaction number** | **Reaction formula** | **Energy loss** | **Type** |
| R1 | e+CO2 → CO + O- | 0 | Attachment |
| R2 | e + CO2 → e + CO2 | 1.24e-5 | Elastic |
| R3 | e + CO2 → e + CO2 | 8.3e-2 | Excitation |
| R4 | e + CO2 → e + CO2 | 1.67e-1 | Excitation |
| R5 | e + CO2 → e + CO2 | 2.52e-1 | Excitation |
| R6 | e + CO2 → e + CO2 | 2.91e-1 | Excitation |
| R7 | e + CO2 → e + CO2 | 3.39e-1 | Excitation |
| R8 | e + CO2 → e + CO2 | 4.22e-1 | Excitation |
| R9 | e + CO2 → e + CO2 | 5.05e-1 | Excitation |
| R10 | e + CO2 → e + CO2 | 2.5e0 | Excitation |
| R11 | e + CO2 → e + CO2 | 7e0 | Excitation |
| R12 | e + CO2 → e + CO2 | 1.05e1 | Excitation |
| R13 | e + CO2 →2e+ CO2+ | 1.33e1 | Ionization |
| R14 | e + O2 → e + O2 | 2e-2 | Excitation |
| R15 | e + O2 → e + O2 | 1.9e-1 | Excitation |
| R16 | e + O2 → e + O2 | 3.8e-1 | Excitation |
| R17 | e + O2 → e + O2 | 5.7e-1 | Excitation |
| R18 | e + O2 → e + O2 | 7.5e-1 | Excitation |
| R19 | e + O2 → e + O2 | 9.7e-1 | Excitation |
| R20 | e + O2 → e + O2 | 1.7e0 | Excitation |
| R21 | e + O2 → e + O2 | 4.5e0 | Excitation |
| R22 | e + O2 → e + O2 | 6e0 | Excitation |
| R23 | e + O2 → e + O2 | 8.4e0 | Excitation |
| R24 | e + O2 → e + O2 | 9.97e0 | Excitation |
| R25 | e + O2 → e + O2 | 1.47e1 | Excitation |
| R26 | e + O2 → O2- | 0 | Attachment |
| R27 | e + O2 → 2e + O2+ | 1.206e1 | Ionization |

4. Results and Discussion

## 4.1 Effect of concentration ratio

The figure 2 below shows the electron density of CO2/O2 under different gas mixture ratios. The different gas mixture ratios are 70% CO2-30% O2, 80% CO2-20% O2, and 90% CO2-10% O2. The simulation is performed under 300 K temperature, 1 bar pressure, and -12 kV applied voltage. Figure 2 shows that the electron density increases when the concentration of CO2 reduces and the O2 increases. The attachment collision reaction of CO2 becomes weak and as a result, the ionization collision reaction becomes strong due to higher electron density. The increase in the ionization collision reaction will intensify the development the streamer discharge. The streamer discharge will take less time to reach the ground electrode. Also, from table 1, the ionization energy of O2 is lower than CO2, which makes O2 to ionize more easily than CO2 [23]. By increasing the O2 concentration ratio, the ionization coefficient increases and the attachment coefficient decreases. Therefore, the streamer discharge will tend to increase as the O2 concentration ratio increases. Hence, reducing the CO2 concentration in the gas mixture increases the electron number density, and the streamer discharge becomes prominent [24].

Similarly, the gas mixture will oppose the streamer discharge to initiate by increasing the CO2. The increase in the CO2 concentration ratio will reduce the streamer discharge and decrease the overall electron number density. When the ionization energy (IE) increase, the value of σBEB bond formation in CO2 has higher value than O2. This indicates the lower stability and higher reactivity of O2 molecules than CO2 molecules[25]. From the simulation results, the electron density in negative streamer discharge is higher than in positive streamer discharge **[18]**. In negative streamer discharge, electrons are responsible for the discharge to occur. Electrons have lower mass than positive ions equipped with higher speed in a gas mixture. Similarly, in a gas mixture, the negative streamer propagates in the opposite direction of the electric field, and the streamer head is equipped with electrons **[13]**. On the other hand, positive streamer discharge propagates in the direction of the electric field with positive ions concentrated on the streamer head. Due to this reason, the electron density in positive streamer is lower as compared with the negative streamer discharge.

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Figure 2 Electron density of CO2/O2 mixture under different concentration ratios

The figure 3 below shows the electric field of CO2/O2 gas mixture under different gas mixture ratios. The electric field shows the same results as of electron density for the CO2/O2 gas mixture. By increasing the O2 ratio in the gas mixture the electric field will increase. The increase in the electric field is due to the increase in the electron density. The increase in the electron density will enhance the secondary electron emission. The enhancement of the secondary electron emission will distort the main electric field and this distortion causes the electric field to increase under different mixture ratio. The electric field in positive streamer is lower as compared with the negative streamer. The increase of the electric field corresponds the higher electron density value. Therefore, when the electron density increases in a streamer discharge the corresponding electric field will also increase. The electron density of positive streamer is lower as compared with the negative streamer. This results a lower value of electric field in a positive streamer discharge.

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Figure 3 Electric field of CO2/O­2 mixture under different ratios

The streamer velocity under different gas mixture has sown in the figure 4 below. The streamer velocity graph shows that streamer velocity depends on the gas concentration ratio. As from the above figure 2, by increasing the O2 concentration ratio the electron density will enhance as well. Due to this reason, the respective streamer velocity will also increase due to the emission of secondary electrons. Similarly, the negative streamer velocity has higher value than positive streamer velocity. In negative streamer, electron drift acts in the direction of the propagation but in positive streamer, electron drift acts against the streamer propagation. Therefore, the propagation speed of negative streamer is higher than the positive streamer [**reference**].

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Figure 4 Streamer velocity of CO*2*/O*2* mixture ratio under different concentration ratios

## 4.2 Effect of applied voltage

The figure 5 below shows the streamer discharge of CO2/O2 mixture gas at different voltage levels and pressures. The 80% CO2-20% O2 ratio has selected for the study of applied voltage. The remaining parameters are constant for the simulation. The figure 5 below depicts that electron density increases by increasing the applied voltage. By increasing the applied voltage, the kinetic energy of the electrons will increase, and hence the electron collision will tend to increase. The streamer discharge will propagate in a shorter time, and the ionization of the gas mixture will increase [26]. Therefore, by increasing the applied voltage, the ionization collision reaction will dominate the attachment collision reaction, and the gas mixture will require less time to breakdown. The electron number density increases from 1.97×1020 to 4.59×1020 when the voltage increases from -8kV to -12kV at 0.35ns, as illustrated in figure 5. The increasing trend of electron density has also observed for the positive streamer when the applied voltage has increased from 8kV to 12kV.

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Figure 5 Electron density (1/m3) of positive and negative streamer discharge at different voltage levels.

The electric field of positive and negative streamer discharge under different voltage levels has shown in figure 6. The electric field increases in positive and negative streamer discharge by increasing the voltage level. The ionization collision in a gas mixture increases with the applied voltage. Due to increase in the ionization collision, the electric field enhances and this result increase in the secondary electron emission. The electric field in positive streamer increases from 3.58×106 to 6.32×106 when the voltage has increased from 8 kV to 12 kV. Whereas in negative streamer the electric field increases from 3.77×106 to 6.88×106 when the voltage has increased from -8 kV to -12 kV.

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Figure 6 Electric field (V/m) of positive and negative streamer under different voltage levels

The streamer velocity under different voltage levels has shown in figure 7 below. The streamer velocity increases with the increase of the applied voltage. The ionization of the gas mixture increases with the increase of the applied voltage and the secondary electron emission enhances. The enhancement of the secondary electron emission causes the streamer velocity to increase. The figure below shows that the negative streamer velocity is higher as compared with the positive streamer velocity. The negative streamer propagates along the electron drift whereas the positive streamer propagates against the electron drift. Hence, due to this reason the negative streamer velocity is higher as compared with the positive streamer velocity.

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Figure 7 Streamer velocity of CO*2*/O*2* mixture ratio under different voltage levels

## 4.3 Effect of applied pressure

Similarly, when the gas mixture pressure increases, the streamer discharge decreases. By increasing the gas pressure, the gas molecules become close to each other, so the ionization collision reaction will be difficult to occur. This also increases the time required by the streamer discharge to move along the electric field. The higher the applied pressure, the lower the streamer discharge to occur, and discharge time will increase [5, 21]. This reduces the ionization collision reaction in a gas mixture as gas molecules are close to each other. By increasing the gas pressure, the mean free path becomes lower, and due to this reason the electrons diffusion also decreases. The decrease in the electron diffusion reduces the collision reaction in a gas mixture, and hence the streamer discharge reduces [21]. Figure 12 illustrates the electron density of negative and positive streamer discharge. The electron density is figure 13 and figure 14 is calculated with the help of equation 1, equation 2 and equation 11. By increasing the pressure, the negative streamer discharge changes its propagation from needle structure to rod-like structure, and the width of the streamer discharge also decreases [21]. The positive streamer discharge rod-like streamer propagation vanishes as the gas pressure increases from 1.5 to 2.5 atm.

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Figure 8

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Figure 9

Figure 74 Electron density of positive and negative streamer discharge at different pressure (1/m3). (a,b,c) represents negative streamer discharge. (d,e,f) represents positive streamer discharge.

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Figure 11

## 4.3 Effect of time

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Figure 12

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Figure 13

The electron density of the CO2/O2 mixture at different time spans is shown in figure 10. The mixed gas ratio is 80% CO2 and 20% O2 as a research study object. The simulation is carried out at 1 atm gas pressure and at 300 K gas temperature. As the configuration is rod to plane electrode and the negative DC high potential is applied to the rod electrode. The value of applied voltage is 10 kV, and -10 kV is used for the positive and negative streamer discharge. From figure 9, it can be seen that initially the value of electron density is low, but with an increases in the time the electron density value increases. The increase in the initial density is due to the increase in the Townsend first ionization coefficient as given in equation (11). The increase in the Townsend first ionization coefficient further increase the electron density and the streamer will begin to propagate in z-axis [22, 27]. From the simulation results, the electron density in negative streamer discharge is higher than in positive streamer discharge [13]. In negative streamer discharge, electrons are responsible for the discharge to occur. Since electrons have lower mass than positive ions and their relative speed is higher in a gas mixture. Similarly, in a gas mixture, the negative streamer propagates in the opposite direction of the electric field, and the streamer head is equipped with electrons [18]. The electron density graph has shown in figure 9. The below graph tells about the negative and positive streamer discharge density at 0.3ns. It can be seen from the below graph that initially the value of electron density is zero but as the streamer propagates the electron density value increases along the arc length. With further propagation in streamer the electron density will reach the maximum value and then falls to again zero. From the graph the electron density peak in negative streamer is higher than positive streamer.

**Figure 89.** Electron density graph between the arc length and electron density (1/m3) at 0.3ns

On the other hand, positive streamer discharge propagates in the direction of the electric field with positive ions concentrated on the streamer head [18]. As a result, the secondary electron emission becomes less effective in positive streamer discharge as compared to negative streamer discharge. The secondary electron emission in a gas mixture occurs due to the Townsend ionization, and this emission is further converted into an avalanche process. The complete discharge will occur in a gas mixture when the streamer reaches the ground electrode [28]. Also, the number of different collision reactions undergo during the streamer initiation and the electron avalanche formation. These include attachment, ionization, excitation, and elastic [5, 12]. The ionization and attachment reaction plays a vital role in the streamer initiation and avalanche formation. The increase in the number of electrons in a gas mixture is due to the electron-neutral molecule ionization reaction [5]. Similarly, the attachment reaction reduces the generated electrons. As the applied voltage is high enough to ionize the gas mixture, therefore the ionization coefficient is higher than the attachment coefficient and hence (α-η) > 0. From the simulation results, it is observed that the negative streamer head is more pointed than the positive streamer head [13]. Hence, the shape of streamer discharge propagation will influence the electron number density. As negative streamer head is equipped with electrons, due to this reason the streamer forms the needle structure and propagate in z direction as shown in figure 9. The electron density at 0.3ns for negative streamer discharge is 4.77×1020, while for positive streamer the value of electron density is 4.43×1020.

**Figure 910.** Electron density of positive and negative streamer discharge at different time (1/m3). (a,b,c) represents negative streamer discharge. (d,e,f) represents positive streamer discharge.

The negative and positive streamer discharge electric field graph has shown in figure 11. From the figure below the maximum electric field peak in positive streamer discharge corresponds to the maximum electron density. The electric field in negative streamer discharge shows the maximum value in beginning of the arc length and then decreases respectively. The negative streamer discharge propagates in the opposite direction of the electric field. Therefore, during the propagation the electric field in the negative streamer channel travels against the propagation till the discharge completes the path from rod to plane electrode. The figure 12 demonstrates the electric field distribution of streamer discharge over various time spans. Figure 12 shows that the electric field follows the same trend as the electron density, i.e., the electric field in negative streamer discharge is greater than in positive streamer discharge [29]. Higher the electric field value in negative streamer discharge indicates that the space charge produced has a greater influence on the electric field [29]. As in negative streamer discharge, the head is mainly formed by electrons, and these electrons significantly distort the electric field near the streamer head [18]. In positive streamer discharge, the streamer head is mainly formed by positive ions, and the relevant speed of positive ions is lower than that of the electrons [18]. Due to lower relevant speed as compared to electrons, the electron density is lower in positive streamer discharge. Therefore, the electric field at the tip of the streamer discharge will be reduced, as illustrated in figure 10. The electric field value for negative streamer discharge at 0.3ns is 6.13×106, whereas for positive streamer discharge, the electric field value is 3.31×106.

**Figure 1011.** Electric field graph between arc length and electric field (V/m) at 0.3ns.

**Figure 1112.** Electric field of positive and negative streamer discharge at different time (V/m). (a,b,c) represents negative streamer discharge. (d,e,f) represents positive streamer discharge

## 4.4 Effect of electrode distance

The figure 18 below shows the electron number density of different electrode distances. The electrode distances of 4mm, 4.5mm, and 5mm are selected for the study, and all other simulation conditions remain unchanged. The simulation results show that with an increase in the electrode distance, the electron density decreases and the streamer discharge takes a longer time to reach the ground electrode. By increasing the electrode distance, the streamer discharge will undergo a longer path to fully develop, which decreases the electron number density at a specific time [30]. By increasing the external electric potential, the streamer discharge will become faster, resulting in a breakdown of the gas mixture in a shorter time. Hence, with the increase in electrode distance, the electron density will decrease at a specific time and reduce the streamer discharge in a gas mixture. The electron density at 4mm of electrode distance is 6.73×1020, which decreases to 5.46×1020 at 5mm of electrode distance.

Furthermore, figure 18 also shows the electron density of positive and negative streamer discharge. The simulation results have revealed that in the case of negative streamer discharge, the streamer form the needle-like formation than in the case of positive streamer discharge. The formation of a needle-like structure in negative streamer discharge increases the electron density at a specific electrode distance. Also, from the simulation results, the positive streamer discharge forms a sphere-like formation, which is responsible for the decrease in the electron density in the positive streamer discharge.

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Figure 125 Electron density of positive and negative streamer discharge at different electrode distances (1/m3). (a,b,c) represents negative streamer discharge. (d,e,f) represents positive streamer discharge

5. Conclusion

In this paper, the streamer discharge initiation and propagation behaviour of CO2/O2 mixture is carried out with the simulation of rod to plane geometry in a two dimensional axis-symmetric space dimension along with plasma physics domain. The paper is distributed in three different sections. The first section is based on the electron transport properties of CO2/O2. The electron transport properties are obtained with the help of the Boltzmann two-term approximation equation. The electron transport properties show that by increasing the amount of CO2 ratio the electron mean energy, longitudinal diffusion coefficient, electron mobility, reduced ionization coefficient, reduced attachment coefficient and EEDF decreases. While at a specific ratio of CO2/O2 the EEDF increases with an increase of reduced electric field (Td). The increase of reduced electric field results in the increase of kinetic energy of a gas mixture and hence the EEDF will also increase. Similarly, the decrease in the electron mean energy with an increase of CO2 in a gas mixture is due to the attachment reaction of CO2 that reduces the ionization reaction in a gas mixture. The longitudinal diffusion coefficient and electron mobility decreases is due to the reason that CO2 is a heavier gas than O2 so diffusion of the gas mixture will reduce by increasing the CO2 content. Similarly, the reduced ionization coefficient decreases as CO2 content increases is due to the reason that CO2 has higher ionization energy than O2 due to this reason more energy is required to breakdown the mixture gas. The increase in the attachment reaction of CO2/O2 mixture is due to the reason that collision cross section of CO2 is lower than O2 that makes it more stable in a gas mixture. The second section is based on the model formation and the establishment of the reaction mechanism for the CO2/O2 gas mixture. The Boltzmann two-term approximation equation, Poisson equation, Gaussian approximation and Townsend first ionization coefficient are used to study the streamer discharge behaviour in a gas mixture.

The third part of the paper is based on the positive and negative streamer discharge simulation results under different conditions. The simulation results show that negative streamer discharge is greater than the positive streamer discharge. The electric field in negative polarity is higher than in positive polarity. The streamer discharge increases with an increase of external applied voltage and decreases with an increase of applied gas pressure. By increasing the voltage electrons gain more energy and streamer propagate more rapidly. Similarly, increasing the pressure in a gas mixture decrease the effective ionization collision between the atoms and as a result the streamer discharge decreases. In the same way by increasing the amount of CO2 in a gas mixture the ionization coefficient decreases, and due to this reason the electron density decreases. The decrease in the electron density results in the decrease of streamer discharge. The total ionization rate also depends on the gas mixture ratio. The total ionization of CO2/O2 decreases by increasing the CO2 ratio in a gas mixture The simulation results also show that in negative polarity the streamer form the rod like formation at the head of the streamer. On the other hand, in positive polarity, the sphere like formation was observed on the head of the streamer. The higher streamer formation, the higher will be ionization of the gas mixture and electron density will increase. The simulation results show that electric field in negative streamer discharge first increases and then decreases with the propagation of the streamer discharge. Similarly, the positive streamer travels in the direction of the electric field, hence the electric field in positive streamer discharge is maximum where the electron density has the maximum peak.

The streamer discharge also depends on the degree of non-uniformity and the electrode length. By increasing the electrode tip radius the streamer discharge decreases and requires more time to travel. Also, by increasing the electrode length the streamer discharge decreases at a specific time. The higher the electrode length the streamer discharge will take more time to reach and hence gas mixture will require more time to break. The streamer velocity in case of positive streamer is higher than in negative streamer. In positive streamer localized electric field and in negative streamer detachment of electrons are responsible for the streamer velocity. The simulation results used in this paper are based on the ideal conditions, which means that external impact like the metal contamination particles are not considered for the study.

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References

[1] C. M. Franck, A. Chachereau, and J. Pachin, "SF 6-free gas-insulated switchgear: Current status and future trends," *IEEE Electrical Insulation Magazine,* vol. 37, no. 1, pp. 7-16, 2020.

[2] P. Billen, B. Maes, M. Larrain, and J. Braet, "Replacing SF6 in electrical gas-insulated switchgear: technological alternatives and potential life cycle greenhouse gas savings in an EU-28 perspective," *Energies,* vol. 13, no. 7, p. 1807, 2020.

[3] X.-C. Yuan *et al.*, "A 3D numerical study of positive streamers interacting with localized plasma regions," *Journal of Physics D: Applied Physics,* vol. 53, no. 42, p. 425204, 2020.

[4] B. Zhang, J. Xiong, L. Chen, X. Li, and A. B. Murphy, "Fundamental physicochemical properties of SF6-alternative gases: a review of recent progress," *Journal of Physics D: Applied Physics,* vol. 53, no. 17, p. 173001, 2020.

[5] R. Zhang, L. Wang, J. Liu, and Z. Lian, "Numerical simulation of breakdown properties and streamer development processes in SF6/CO2 mixed gas," *AIP Advances,* vol. 12, no. 1, p. 015003, 2022.

[6] L. Lin, X. Meng, H. Mei, and L. Wang, "Influence of AC and DC composite voltage on positive streamer discharge," *IEEE Transactions on Dielectrics and Electrical Insulation,* 2023.

[7] S. Kumar, T. Huiskamp, A. Pemen, M. Seeger, J. Pachin, and C. M. Franck, "Electrical breakdown study in CO 2 and CO 2-O 2 Mixtures in AC, DC and pulsed electric fields at 0.1–1 MPa pressure," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 28, no. 1, pp. 158-166, 2021.

[8] T. Huiskamp, C. Ton, M. Azizi, J. Van Oorschot, and H. Höft, "Effective streamer discharge control by tailored nanosecond-pulsed high-voltage waveforms," *Journal of Physics D: Applied Physics,* vol. 55, no. 2, p. 024001, 2021.

[9] B. Bagheri, J. Teunissen, and U. Ebert, "Simulation of positive streamers in CO2 and in air: the role of photoionization or other electron sources," *Plasma Sources Science and Technology,* vol. 29, no. 12, p. 125021, 2020.

[10] X. Li, A. Sun, and J. Teunissen, "The effect of photoionization on positive streamers in CO2 studied with 2D particle-in-cell simulations," *arXiv preprint arXiv:2304.01531,* 2023.

[11] R. Marskar, "A 3D kinetic Monte Carlo study of streamer discharges in CO2," *arXiv preprint arXiv:2312.02634,* 2023.

[12] S. Nijdam, J. Teunissen, and U. Ebert, "The physics of streamer discharge phenomena," *Plasma Sources Science and Technology,* vol. 29, no. 10, p. 103001, 2020.

[13] X. Li, A. Sun, and J. Teunissen, "A computational study of negative surface discharges: Characteristics of surface streamers and surface charges," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 27, no. 4, pp. 1178-1186, 2020.

[14] X. Yan, X. Zhou, Z. Li, Y. Qian, and G. Sheng, "Surface Discharge Characteristics and Numerical Simulation in C4F7N/CO2 Mixture," *Applied Sciences,* vol. 13, no. 3, p. 1409, 2023.

[15] F. Boakye-Mensah, N. Bonifaci, R. Hanna, and I. Niyonzima, "Implementation of a cathode directed streamer model in Air under different voltage stresses," *arXiv preprint arXiv:2010.07570,* 2020.

[16] N. Y. Babaeva, G. Naidis, D. Tereshonok, V. Tarasenko, D. Beloplotov, and D. Sorokin, "Formation of wide negative streamers in air and helium: the role of fast electrons," *Journal of Physics D: Applied Physics,* vol. 56, no. 3, p. 035205, 2022.

[17] X. Li, A. Sun, G. Zhang, and J. Teunissen, "A computational study of positive streamers interacting with dielectrics," *Plasma Sources Science and Technology,* vol. 29, no. 6, p. 065004, 2020.

[18] H. Francisco, B. Bagheri, and U. Ebert, "Electrically isolated propagating streamer heads formed by strong electron attachment," *Plasma Sources Science and Technology,* vol. 30, no. 2, p. 025006, 2021.

[19] Z. Wang, A. Sun, and J. Teunissen, "A comparison of particle and fluid models for positive streamer discharges in air," *Plasma Sources Science and Technology,* vol. 31, no. 1, p. 015012, 2022.

[20] A. K. Pandey, P. Singh, M. S. Khan, and J. K. Singh, "Determination of Insulating Properties of SO 2 gas from BOLSIG+ Calculated Swarm Transport Coefficients," in *2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, 2021: IEEE, pp. 137-142.

[21] X. Ou, L. Wang, J. Liu, and X. Lin, "Numerical simulation of streamer discharge development processes with multi-component SF6 mixed gas," *Physics of Plasmas,* vol. 27, no. 7, 2020.

[22] R. Talviste, P. Paris, J. Raud, T. Plank, and I. Jõgi, "Experimental determination of first Townsend ionization coefficient in mixtures of He and N2," *Journal of Physics D: Applied Physics,* vol. 54, no. 32, p. 325202, 2021.

[23] E. Carbone *et al.*, "Data needs for modeling low-temperature non-equilibrium plasmas: the LXCat project, history, perspectives and a tutorial," *Atoms,* vol. 9, no. 1, p. 16, 2021.

[24] Y. Zhang, B. Xia, J. Ran, K. Davey, and S. Z. Qiao, "Atomic‐level reactive sites for semiconductor‐based photocatalytic CO2 reduction," *Advanced Energy Materials,* vol. 10, no. 9, p. 1903879, 2020.

[25] J. Scherschligt *et al.*, "Quantum-based vacuum metrology at the National Institute of Standards and Technology," *Journal of Vacuum Science & Technology A,* vol. 36, no. 4, 2018.

[26] D. N. Saleh, Q. T. Algwari, and F. K. Amouri, "Modeling the dependence of the negative corona current density on applied voltage rise time," *Physics of Plasmas,* vol. 27, no. 7, 2020.

[27] R. Talviste, P. Paris, J. Raud, T. Plank, K. Erme, and I. Jõgi, "Experimental determination of the first Townsend ionization coefficient in mixtures of Ar and N2," *Journal of Physics D: Applied Physics,* vol. 54, no. 46, p. 465201, 2021.

[28] A. F. Al-rawaf and T. H. Khalaf, "Simulation of positive streamer discharges in transformer oil," in *Journal of Physics: Conference Series*, 2022, vol. 2322, no. 1: IOP Publishing, p. 012066.

[29] J. Jánský, D. Bessiéres, R. Brandenburg, J. Paillol, and T. Hoder, "Electric field development in positive and negative streamers on dielectric surface," *Plasma Sources Science and Technology,* vol. 30, no. 10, p. 105008, 2021.

[30] J. Zhang, Y. Wang, D. Wang, and D. J. Economou, "Numerical simulation of streamer evolution in surface dielectric barrier discharge with electrode-array," *Journal of Applied Physics,* vol. 128, no. 9, 2020.