Numerical Investigation of Positive and Negative Streamers in CO_2/O_2 Mixtures as Eco-Friendly Alternatives to SF_6 for High Voltage Insulation

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(2024)

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Supervisor: Dr. Muhammad Farasat Abbas

U.S Pakistan Center for Advanced Studies in Energy (USPCAS-E)

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS Thesis written by Mr. Hafiz Muhammad Tahir Nisar (Registration No. 000000364708), of U.S Pakistan Center for Advanced Studies in Energy (USPCAS-E) has been vetted by undersigned, found complete in all respects as per NUST Statutes/ Regulations/ Masters Policy, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of Masters degree. It is further certified that necessary amendments as point out by GEC members and foreign/ local evaluators of the scholar have also been incorporated in the said thesis.

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MASTER'S THESIS WORK

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This is to certify that the research work presented in this thesis, entitled "Numerical Investigation of Positive and Negative Streamers in CO_2/O_2 Mixtures as Eco-Friendly Alternatives to SF_6 for High Voltage Insulation" was conducted by **Mr. Hafiz Muhammad Tahir Nisar** under the supervision of **Dr. Muhammad Farasat Abbas**.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the US-Pakistan Center for Advanced Studies in Energy in partial fulfillment of the requirements for the degree of Master of Science in Electrical Power Engineering, Department of US-Pakistan Center for Advanced Studies in Energy National University of Sciences and Technology, Islamabad.

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DEDICATION

I dedicate this whole effort to our parents and teachers who supported and helped us throughout our learning and studying span and enabled us to reach this stage of life by means of their hardworking precious prayers and love which make it possible to get this goal today. This thesis is dedicated to all those who believe in richness of learning.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

Symbols

E/N	Electron to neutral ratio
Td	Reduced electric field
α	Ionization coefficient (m^{-1})
n_e	Electron density (m^{-3})
μ_e	Electron mobility (m^2/Vs)
D	Diffusion coefficient (m^2/s)
R_e	rate of generation and loss processes ($m^{-3}s^{-1}$)
$\mathbf{E}$	Electric field (V/m)
w_k	Mass faction of the species k,
R_k	Rate expression of generation
ρ	Gas mixture density
ε_r	Relative permeability
ε_0	Absolute permeability,
q	Elementary charge
∇V	Gradient of the electric potential.
s_0	Initial distribution particle radius

Abbreviations

GWP	Global Warming Potential

ABSTRACT

SF_6 is commonly used as gaseous insulation media in high voltage equipment, but it has high GWP and urgently needs to be replaced with eco-friendly alternatives. CO_2-based mixtures have shown promising results as SF_6 alternatives. Streamers form the initial phase of electrical breakdown have become important for the reliable design of high-voltage equipment based on gaseous insulation. In this thesis, the influence of concentration ratio (90%CO_2/10%O_2, 80%CO_2/20%O_2, and 70%CO_2/30%O_2), applied voltage (±8kV, ±10kV, and ±12kV), pressure (1.5, 2.0, and 2.5 bar), and gap distance (4mm, 4.5mm, and 5mm) on positive and negative streamer formation and propagation is investigated in detail using a 2D axis-symmetric simulation model. Considering the low probability in gas mixtures with higher concentrations of CO_2, photoionization has excluded, and background ionization has used for generating free electrons along with the Townsend ionization equation and the Gaussian approximation for the initial electron density distribution. The simulation results show that by increasing the O_2 concentration in CO_2 the the electron density, electric field, and streamer velocity enhances under positive and negative polarities. The σ (collision cross section) value of O_2 is greater than CO_2 at the specific ionization energy, indicating that O_2 molecules in a gas mixture have higher reactivity and lower molecular stability. The negative streamer has an overall high electron density as compared to the positive streamer. To understand the effect of applied voltage, pressure, and gap distance only 80%CO_2/20%O_2 concentration ratio was chosen. By increasing the applied voltage the electron density, electric field, and streamer velocity increase. Furthermore, a decreasing trend of electron density, electric field, and streamer velocity has observed by increasing the gas pressure and the electrode distance.

Keywords: Electrical breakdown, Streamer discharge, 2D simulation model, SF_6, CO_2, O_2

CHAPTER 1: INTRODUCTION

1.1 SF_6 based circuit breakers

Sulfur hexafluoride (SF_6) is generally used as insulation medium gas in different high voltage equipment and in a medium and high voltage insulated lines. The gas plays a crucial role in high-voltage fault protection and insulation. But, SF_6 has a remarkably high global warming potential (GWP), making it one of the environment destructive gas [1, 2]. Its GWP index is about 23,500 times more than CO_2[3]. As a result, it is essential to replace SF_6 with environmentally friendly gases or gas mixtures that offer similar properties[4]. CO_2 has demonstrated significant potential in switching performance and could be a viable alternative to SF_6, either in its pure form or combined with other substances like C_4F_7N, CF_3I, or $C_5F_{10}O$ [5, 6].

1.2 Motivation for SF_6 alternatives

Today most of the circuit breakers and switchgears are SF_6 based and used in different high voltage lines. SF_6 gas is not an environment friendly. Due to this reason, the earth temperature is increasing with a passage of time. Therefore, it is important to protect the earth temperature and reduce the carbon footprints by moving towards the SF_6 alternatives. Some of the alternatives are composed of a mixture [7]. These composite mixtures have relatively low dielectric strength than SF_6 but the carbon emission is very less when compare to the pure SF_6. Before using the gas mixture as an alternative, it is important to conduct various experiments to ensure the dielectric strength will withstand the high voltage. Simulations and experiments help to understand the behaviour of the gas mixture and hence the mixture can be used for the SF_6 alternative [8].

1.3 Streamer discharge in a gas mixture

The streamer discharge in a gas mixture is responsible for the breakdown of the gas mixture. As the applied potential generates the effective potential to breakdown the gas mixture and as a result, the gas mixture begins to break. A streamer discharge is responsible for breakdown in a gas mixture, in the same way partial discharge is responsible for breakdown in solid. Several conditions must be fulfilled for the streamer discharge to occur in a gas mixture. These conditions are high voltage, pressure, gap distance and insulation boundary. Corona discharge is also a type of discharge but it occurs in open environment when the ionization potential in higher than the air ionization potential. Due to this reason, corona discharge occurs [9]. On the other hand, streamer discharge does not occur in an open environment. It occurs in a close environment and forms branches like structure in a gas mixture. In a gas mixture, when the applied voltage excites the gas molecules and as result the electrons in the outermost shell are energize. This creates the avalanche of electrons in a gas mixture and hence the streamer begins to initiate. Once the streamer discharge initiate in a mixture, the breakdown will begin to start. As the streamer discharge approaches from one electrode to the other then a complete discharge will occur in a gas mixture [10].

1.4 Physics of streamer discharge

Streamer discharge plays a critical role in the breakdown of the gas mixture. By controlling the ionization potential and other parameters, the streamer discharge initiation and propagation can be controlled easily. Depending on the propagation, two types of streamer discharge occur in a gas mixture. Each has own initiation and propagation characteristics. One is positive streamer discharge and other is negative streamer discharge. Positive streamer is more common in real life than the negative streamer [11]. Streamer discharge occur in a thunder lightning as the air mixture in atmosphere begin to ionize. The atmosphere has 78% N_2 and 21% O_2, due to this mixture when the lightning occur, the mixture ionizes and the streamer begins to form. The streamer discharge travelling from ground to the upward is known as positive streamer and other one that travels from upward to the ground is called as negative streamer [12]. Therefore, when simulating positive and negative streamer discharge the direction of propagation must define.

1.4.1 Positive streamer charge

Positive streamer discharge also known as anode discharge because it initiates from positive side of electrode (anode) propagates towards the negative side (cathode). The streamer head is equipped with positive ions. The direction of propagation is along the electric field but against the electron drift. A constant source of electrons is required for the initiation of positive streamer. Due to majority of positive charges on the streamer head, the propagation velocity is low. Therefore, electron source plays a critical role in initiating the positive streamer in a gas mixture [13]. The positive streamer propagation has shown in figure below.

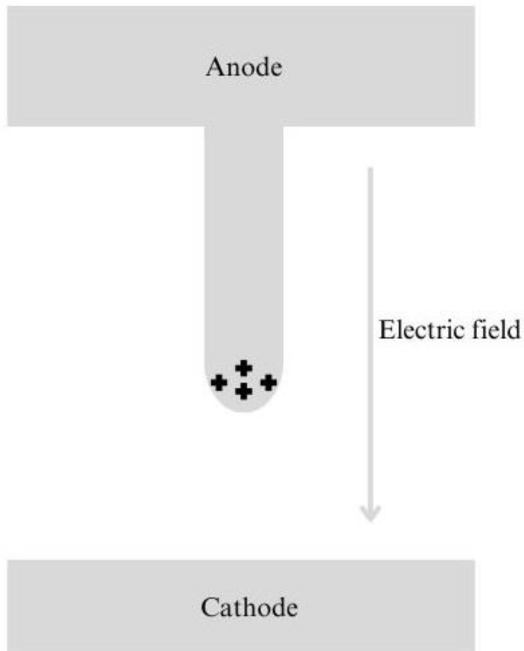

Figure 1.1: Positive streamer propagation

1.4.2 Negative streamer charge

Negative streamer on the other hand, known as cathode discharge because it initiates from the cathode (negative) and propagates towards the anode (positive). The streamer head contains majority of electrons. As the mass of electron is lower than the positive ions due to this reason the propagation speed of negative streamer is higher than the positive streamer. The negative streamer propagates in the same direction of an electron drift but against the electric field direction as shown in the figure 2 below. Hence, the ionization of the gas mixture in negative streamer is more than in positive streamer by keeping all the parameters remain constant [14].

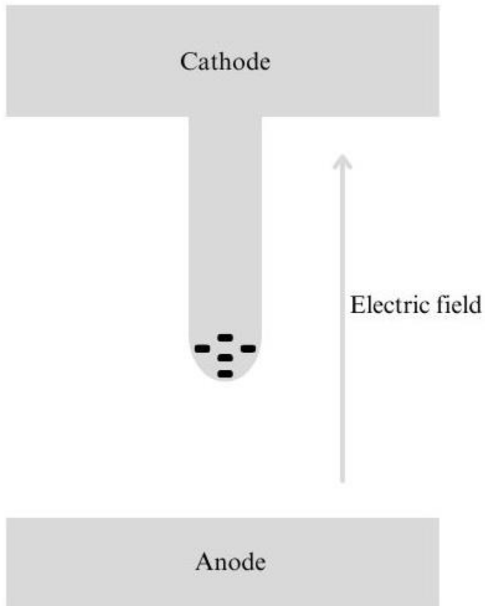

Figure 1.2: **Negative streamer propagation**

1.5 Townsend ionization coefficient

The Townsend ionization coefficient is the most important coefficient used for the simulation of streamer discharge. The Townsend ionization coefficient helps to understand the secondary electron emission behaviour in a gas mixture. The secondary electron emission plays a crictical role in a streamer discharge. Without the Townsend ionization coefficient, it is not possible to simulate the streamer discharge. By changing the coefficients, the secondary electron emission increases or decreases. The secondary electron emissions from Townsend ionization coefficient will help to ignite the plasma and the streamer discharge process will begin to initiate. Once the plasma has ignited, it will initiate the streamer discharge. The secondary electron emission will convert into the avalanche process and this avalanche process will convert into the streamer process [15].

1.6 Challenges for SF_6 alternatives

The replacement of SF_6 based circuit breakers with the alternatives may have challenges to address. Following challenges may arrive when replacing SF_6 with the alternative.

- The SF_6 gas has the highest breakdown strength and due to this reason is it important to choose the alternative that has the same breakdown strength and has the low global warming potential.
- The manufacturing cost of the new alternative is another challenge for the electrical power companies.
- The toxicity and the reactivity of the alternative gas should be lower than that of SF_6.
- The transportation cost of the SF_6 alternative.
- The environmental behaviour of the SF_6 alternative.

1.7 Research questions

1. Streamer discharge propagation and its behavior with the insulation medium.
2. How the streamer velocity influence by the positive and negative streamer discharge?
3. What are the other parameters that affect the streamer discharge propagation?
4. The formation of electron density and electric field during the streamer discharge propagation in an insulating medium.

1.8 Structure of Thesis

The thesis has divided into five major chapters. The first chapter is the introduction of the thesis in which the streamer discharge process has discussed in detail. The second chapter is the literature review in which the previous literature has discussed thoroughly. The third chapter of thesis is based on the modelling and simulation along with the equations and reactions used in the simulation process. The fourth chapter is related to the results and discussion of the simulation. The result chapter has divided into two major portions. The electron transport properties have discussed in first portion and the simulation results in the second portion. The last chapter is the conclusion of the whole thesis.

SUMMARY

This chapter is the introduction of the streamer discharge phenomenon for the high voltage circuit breakers and switchgears. This chapter covers the physics of streamer discharge along with the behaviour in a gas mixture. The positive and negative streamer discharge has discussed along with the generation of secondary electrons for the plasma formation. The formation of streamer discharge in a gas mixture and the propagation has also discussed. The streamer discharge propagation depends on the secondary electron emission and hence by controlling these electrons the propagation can be controlled easily. Also, the current trend of SF_6 based high voltage circuit breakers and switch gears have discussed and the need for the replacement of SF_6 with alternatives. In the last challenges have discussed based on the SF_6 alternatives.

CHAPTER 2: LITERATURE REVIEW

2.1 Experiment based CO_2/O_2 mixed gases

The literature has shown that different authors have carried out streamer discharge experiments based on CO_2 mixed gases. Lin et al. conducted an experiment on positive streamer discharge using the AC and DC composite voltage. The key characteristics of positive streamers, such as streamer propagation, streamer velocity, and luminous intensity have thoroughly discussed. The experiment results demonstrated that the positive streamer discharge characteristics under the AC and DC source voltage mixtures differ from those under pure DC voltage. The positive streamer discharge depends on the phase of the potential[16]. In this work, the authors focused on the composite voltage used for the streamer discharge initiation and propagation. By adjusting the voltage, the different characteristics of the streamer discharge have observed. The authors also concluded that by changing the polarity of the applied the streamer discharge characteristics changes. Therefore, from the above experiment, it has concluded that streamer discharge depends on the voltage polarity and the streamer discharge characteristics also changes.

Kumar et al. also performed the experiment on CO_2/O_2 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 electric field, the breakdown electric field has 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 of negative impulse voltage is more than the positive impulse voltage in a weak and non-uniform electric field [17]. The authors in this experiment highlighted the impact of weak and non-uniform electric field. The role of electric filed is crucial in a streamer discharge formation. Higher value of non-uniform electric field, more the discharge occur in a gas mixture. Furthermore, the weak non-uniformity of the electric field does not have must impact on the streamer discharge propagation. Furthermore, the authors also concluded that by changing the voltage type the streamer discharge changes and hence the propagation changes.

Similarly, Huiskamp et al. worked on the effective streamer discharge propagation with the help of a nanosecond pulsed waveform generator. The propagation of the streamer can be regulated by adjusting the waveform, the pulse rise time has minimal impact on its propagation. However, the streamer velocity is affected significantly by changes in the rise and fall time of the pulsed waveform generator [18]. In this experiment, the authors used the pulsed waveform generator for the high voltage source. By using the pulsed waveform generator, the streamer velocity can be controlled easily. For the pulsed generator the rise and fall time is important for the streamer discharge parameters. The rise time of pulsed waveform is the time in which the wave reaches the highest peak. On the other hand, fall time is the time in which the wave approaches to the lowest amplitude.

2.2 Simulation based CO_2/O_2 mixed gases

Different authors have also performed the streamer discharge simulation of CO_2 mixed with other gases. Bagheri et al. performed the simulation of positive streamer discharge in CO_2 with and without air mixture. As the photoionization mechanism in CO_2 has a low probability, therefore background ionization mechanism has been used for the study of the positive streamer in this simulation model [19]. The simulation results of this thesis show that streamer propagation is less dependent on the background ionization level. Other factors, such as electric field, applied voltage, electron mobility (μ), and ionization coefficient (α), are strongly depends on streamer propagation. The effect of photoionization in CO_2 is low and due to this reason, it is preferable to use the background ionization. In the background ionization, the initial electron density value is high. The plasma initiates easily because of the high initial electron density and the process of the streamer discharge continue. By changing the background ionization, the streamer discharge increases or decreases in a gas mixture.

Furthermore, Li and other co-authors worked on the streamer discharge simulation in CO_2 using the particle-in-cell model. They proposed that photoionization in CO_2 is much weaker when compared with air because the probability of ionization photons in CO_2 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 a positive streamer in CO_2 depends on the electric field value [20]. In this simulation, the authors concluded that the probability of photoionization in CO_2 is low. The low probability of photoionization in CO_2

reduces the electric field. Hence, the background ionization can use to enhance the electric field and the streamer discharge formation in a gas mixture.

Similarly, Marskar performed the streamer discharge simulation in CO_2 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 propagation and initiation of streamer discharge. The electron attachment plays a critical role in negative streamer whereas photoionization in positive streamer discharge. The author performed the computational analysis and concluded that photoionization in CO_2 helps the positive streamer to propagate in a gas mixture [21]. CO_2 is considered as the prominent alternative gas as from the above literature. As the photoionization in CO_2 is weak, so background ionization has been selected as an alternative breakdown mechanism [9, 22]. From the above simulation work, it has concluded that each of the streamer discharge has own characteristics. Positive streamer depends on the photoionization whereas negative streamer depends on the attachment. The initiation and propagation of streamer discharge depends on these two parameters.

2.3 CO_2 mixture with other SF_6 alternatives

Literature has shown the different studies on the breakdown characteristics of CO_2 with other compounds including the breakdown characteristics, streamer discharge characteristics, study of swarm parameters, partial discharge behaviour, surface roughness and dielectric coating, surface streamer interaction and breakdown in GIS (Gas Insulated Switchgear) [6]. Nijdam et al. worked on the streamer discharge propagation in a medium and the scaling of streamers with density [9]. Li, Sun and Teunissen contributed the work of streamers and the interaction with the surface [23]. Similarly, Yan worked on the discharge characteristics of C_4F_7N/CO_2 gas mixture [24].

Boakye-Mensah propoesed the results based on the cathode directed discharge with external applied votlage in air [25]. The study also revealed that influence of streamer on electron density during propagation is still missing in different literatures. For the negative streamer discharge electrons are abundant and streamer head is carried with electrons, while in positive streamer discharge the streamer head is carried with positive ions [22, 26, 27]. In this work first calculate the swarm parameters of CO_2 and O_2 by solving the Boltzmann two term approximation equation. CO_2/O_2 mixtures are selected as the study object in this work [11].

SUMMARY

In this chapter, the thorough literature review has conducted for the positive and negative streamer discharge. Starting from the experiments of CO_2 based mixture in which different authors have performed different techniques. From the literature review, it has observed that various authors have contributed to understand the physics and behaviour of streamer discharge. After that, the simulation based CO_2 mixtures for understanding the streamer discharge. The authors also performed various simulations based on the CO_2 mixture to understand the streamer discharge behaviour. In the same way, the mixture of CO_2 with other SF_6 alternatives have also performed to know the working of streamer discharge in these mixtures. Hence, a thorough literature review has conducted for the understanding of the streamer discharge phenomenon.

CHAPTER 3: SIMULATION AND MATHEMATICAL MODELLING

3.1 Physical model

The physical model has shown in figure 1 below. As the size of high voltage insulation equipment is quite large and complex structure is involved in it. Due to this reason, it is not necessary to simulate the entire structure to save the simulation time. For this purpose, rod to plane electrode geometry can be used for the simulation and the streamer initiation process in a small area. The rod to plane electrode also generates the non-uniform electric field inside the gap [6]. Before the streamer initiation only few freely movable charge particles are available in the absence of the electric field. After applying the voltage, the charge particles (electrons and ions) increase due to the multiple reaction mechanisms (ionization, attachment, excitation, detachment and recombination) [28]. The electrons to move quickly from the rod to the grounded plane electrode due to the high electric field. The background gas molecules and electrons collide and secondary emission of electron avalanche occurs. Meanwhile, the electrons will also combine with the neutral molecule or with the positive ion and hence the mechanism of attachment and recombination will start. As a result the electron avalanche process will form and will convert into a streamer and hence cases the gap to break down [6].

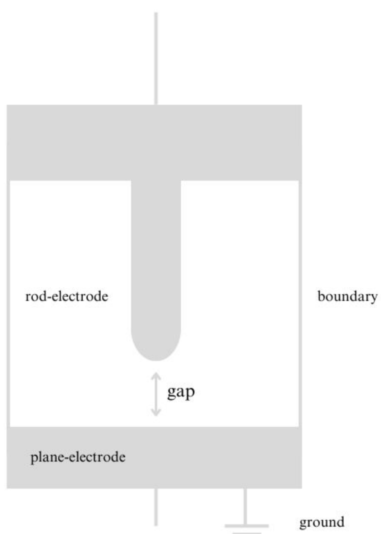

Figure 3.1: Physical model for streamer discharge

3.2 Simulation model

The simulation model of CO_2/O_2 has shown in Figure 1. In figure 1 below, (**a**) is a rod electrode with a diameter of 2mm, (**b**) is the plane electrode with a length of 4mm, and (**c**) is the streamer discharge boundary as well as for the CO_2/O_2 mixture with a length of 6mm. The distance between the rod tip and the plane electrode is 4mm. The entire simulation model has covered with a free mesh triangular network. To obtain more accurate results, the mesh near the rod electrode is significantly increased [6]. Furthermore, the Gaussian approximation is used for the initial density distribution, as explained in the parameter settings section [29].

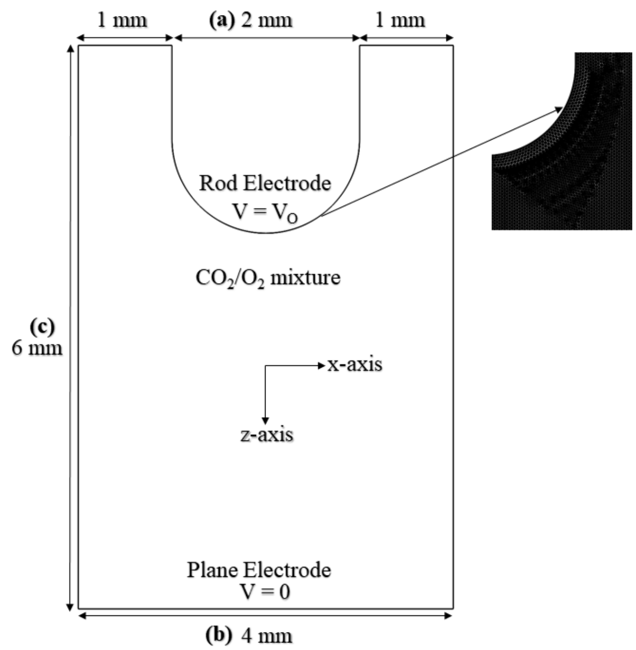

Figure 3.2: Streamer discharge plasma model

The streamer discharge model of CO_2/O_2 is based on the understanding of various parameters. Different studies have shown the simulation-based fluid modeling of CO_2 mixed with other gases (O_2, N_2, SF_6) to understand the behaviour of the different parameters on the streamer discharge[6, 30]. This thesis focuses 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 the CO_2/O_2 mixture.

The simulation of streamer discharge through fluid modeling involves the utilization of several equations, including the fundamental drift-diffusion equation and the Poisson equation. A popular formulation for simulating streamer discharge in a background gas in fluid modeling relies on the drift-diffusion technique. This technique utilizes 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 [31, 32].

$$\frac{\partial n_e}{\partial t} + \nabla.(-n_e\mu_e\boldsymbol{E} - D_e\nabla n_e) = R_e \qquad (1)$$

where n_e is the electron density (m^{-3}), μ_e is the electron mobility (m^2/Vs), D is the diffusion coefficient (m^2/s), **E** is the electric field (V/m), R_e is the rate of generation and loss processes ($m^{-3}s^{-1}$) and t stand for time.

The initiation of the streamer process in a background gas is represented by their respective rates, as given in various equations. The electron source term equation is based on an electron impact ionization, as given below [25].

$$R_{ion} = \alpha n_e \mu_e E \qquad (2)$$

Where α (m^{-1}) is the Townsend ionization coefficient.

Similarly, the rate for the attachment and detachment of electrons to the electronegative gas (O_2, CO_2, SF_6, etc.) is represented by the following equations [25].

$$R_{att} = \eta n_e \mu_e E \qquad (3)$$

Where η (m^{-1}) is the attachment coefficient.

Equations (5-10) represent the generation and loss of ions and electrons in a background gas such as CO_2/O_2. To understand the variation in ions with respect to the time, the ion drift-diffusion is used as given below [31].

$$\rho\frac{\partial w_k}{\partial t} = \nabla.(\rho w_k V_k) + R_k \qquad (4)$$

w_k represents the mass faction of the species k, R_k represents the rate expression of generation and ρ represents the gas mixture density.

For the streamer to initiate and develop, the Poisson equation is important in determining the electric field distributions due to the formation of space charge in the streamer development process. The Poisson equation is represented by the following equation [6].

$$\nabla(\varepsilon_r\varepsilon_0\nabla V) + q\left(n_p - n_e - n_n\right) = 0 \qquad (5)$$

ε_r represents the relative permeability, ε_0 is the absolute permeability, q is the elementary charge and ∇V represents the gradient of the electric potential.

3.3 Parameter settings

The rod electrode, as shown in Figure 1 is (a) and the plane electrode is (b). The boundary conditions for the rod electrode are given by the equation.

$$V = V_O \quad (6)$$

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

$$V = 0 \quad (7)$$

3.3.1 Insulation and zero charge boundary

It has assumed that no charge on the boundary and zero electron flux is on the boundary for the boundary condition of CO_2/O_2 as shown in above figure 1. These two boundary conditions are represented by the equations given below [6].

$$n.D = 0 \quad (8)$$

$$-n.\Gamma_e = 0 \quad (9)$$

3.3.2 Background equations and initial density distribution

The streamer propagates within the boundary of the simulation under the background gas mixture. The streamer propagation can be controlled by controlling the Gaussian distribution parameters. The Gaussian approximation for initial density distribution is represented by Equation 10, as given below [24].

$$n = n_{max} \times \left(-\frac{r - r_0}{2s_0^2}\right)^2 - \left(\frac{z - z_0}{2s_0^2}\right)^2 \quad (10)$$

Where r and z is the coordinates of streamer discharge along the x and y-axis. r_0 and z_0 are the rod electrode coordinates. s_0 is the initial distribution particle radius. The maximum initial electron density in the beginning is at the electrode tip and hence the propagation of the streamer along the z-axis will become easy.

Townsend's first ionization coefficient has used to determine the secondary electron emissions from the electron, impact reaction for the secondary emission of electrons. The Townsend first ionization coefficient is given below in equation 11 [33].

$$\alpha = A \times P \times e^{(-\frac{BP}{E})} \qquad (11)$$

Where A and B are the constants with a constant value of 5 and -250 respectively. P represents the pressure in Torr, and E represents the electric field (V/m).

3.3.3 Initial conditions and reaction mechanism

For the simulation of streamer discharge in a CO_2/O_2 mixture, the initial electron density value has been selected based on the accurate simulation results. The initial value of electron density is 1×10^{22} (m^{-3}). The initial ion density value (CO_2^+, O_2^+, O_2^- etc.) is taken as 1×10^{19} (m^{-3}). The initial value of electron and ion mobility is 1.2×10^5 (m^2/V. s) and 1.3×10^2 (m^2/V. s) respectively. The initial value of longitudinal and transverse electron diffusion is between 1800 and 2190 (m^2/s). The initial electric potential is 0 V, and the initial electron energy is 3 eV respectively [6].

3.4 Reaction mechanism

The reaction mechanism for the streamer discharge in CO_2/O_2 is presented in **Table 3.1** as given below. The reactions are used to simulate streamer discharge development in a CO_2/O_2 gas mixture. Reaction R1-R27 has been taken from the LXCat database [34]. In this research, four different reactions – elastic, excitation, attachment, and ionization – are used to study the insulation properties of CO_2 and O_2 gas mixtures. Reaction R2 is the elastic collision reaction of CO_2. Reactions R13 and R27 are the ionization reactions of CO_2 and O_2. R1 and R26 are the attachment reactions of CO_2 and O_2 [31]. The rest of the reactions are the excitation reactions. In this research, the focus is to understand the impact of the electronegative gas and the corresponding reactions on the streamer formation in the CO_2/O_2 gas mixture.

Table 3.1: Reaction mechanism and collision cross-section

Reaction number	Reaction formula	Energy loss (eV)	Type
R1	$e + CO_2 \rightarrow CO + O^-$	0	Attachment
R2	$e + CO_2 \rightarrow e + CO_2$	$1.24e^{-5}$	Elastic
R3	$e + CO_2 \rightarrow e + CO_2$	$8.3e^{-2}$	Excitation
R4	$e + CO_2 \rightarrow e + CO_2$	$1.67e^{-1}$	Excitation
R5	$e + CO_2 \rightarrow e + CO_2$	$2.52e^{-1}$	Excitation
R6	$e + CO_2 \rightarrow e + CO_2$	$2.91e^{-1}$	Excitation
R7	$e + CO_2 \rightarrow e + CO_2$	$3.39e^{-1}$	Excitation
R8	$e + CO_2 \rightarrow e + CO_2$	$4.22e^{-1}$	Excitation
R9	$e + CO_2 \rightarrow e + CO_2$	$5.05e^{-1}$	Excitation
R10	$e + CO_2 \rightarrow e + CO_2$	$2.5e^{0}$	Excitation
R11	$e + CO_2 \rightarrow e + CO_2$	$7e^{0}$	Excitation
R12	$e + CO_2 \rightarrow e + CO_2$	$1.05e^{1}$	Excitation
R13	$e + CO_2 \rightarrow 2e + CO_2^+$	$1.33e^{1}$	Ionization
R14	$e + O_2 \rightarrow e + O_2$	$2e^{-2}$	Excitation
R15	$e + O_2 \rightarrow e + O_2$	$1.9e^{-1}$	Excitation
R16	$e + O_2 \rightarrow e + O_2$	$3.8e^{-1}$	Excitation
R17	$e + O_2 \rightarrow e + O_2$	$5.7e^{-1}$	Excitation
R18	$e + O_2 \rightarrow e + O_2$	$7.5e^{-1}$	Excitation
R19	$e + O_2 \rightarrow e + O_2$	$9.7e^{-1}$	Excitation
R20	$e + O_2 \rightarrow e + O_2$	$1.7e^{0}$	Excitation
R21	$e + O_2 \rightarrow e + O_2$	$4.5e^{0}$	Excitation
R22	$e + O_2 \rightarrow e + O_2$	$6e^{0}$	Excitation
R23	$e + O_2 \rightarrow e + O_2$	$8.4e^{0}$	Excitation
R24	$e + O_2 \rightarrow e + O_2$	$9.97e^{0}$	Excitation
R25	$e + O_2 \rightarrow e + O_2$	$1.47e^{1}$	Excitation
R26	$e + O_2 \rightarrow O_2^-$	0	Attachment
R27	$e + O_2 \rightarrow 2e + O_2^+$	$1.206e^{1}$	Ionization

SUMMARY

In this chapter, the main methodology of the thesis has discussed in detail. In the methodology, the 2-D axisymmetric model has developed with the help of the FEM (Finite Element Method). By adopting the mesh in the model in the plasma domain with the help of different equations, the streamer discharge has formed in the model. The equations include the electrostatic equation, Poisson's equation, Gaussian approximation equation and the drift diffusion equation. Furthermore, the reactions used for the simulation helps to understand the effect of each reaction on the simulation behaviour. These reactions have taken from the LXCat database.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Electron transport parameters

4.1.1 Electron mean energy and reduced electric field

The figure below shows the electron mean energy and reduced electric field. The reduced electric field is along the x-axis, and the electron mean energy is along the y-axis. At 300 K, the electron mean energy trend along the various E/N ratios has taken. As shown in figure 4-1, the lower limit below 500 Td produces nearly identical results. The energy of mixed gas increased when the value of reduced electric field increased to 1000 Td. The value of mean energy increases as the amount of O2 in the atmosphere increases. The higher the value of E/N, the easier it is to ionize the gas mixture, and thus the streamer will initiate. [35]. Under the same value of reduced electric field (E/N), the higher the amount of oxygen gas the higher will be the electron mean energy. It means that the ionization process in a gas mixture will increase and hence the streamer will also increase. On the other hand, by increasing the amount of CO_2 in a mixture gas the electron mean energy will reduce. Since the interruption properties of CO_2 is better than O_2 and as CO_2 has higher atomic mass as compared with O_2 [36]. This makes CO_2 more heavier gas as compared with O_2. Therefore, by increasing the concentration ratio of O_2 the electron mean energy will reduce as shown below in **Figure 4.1**.

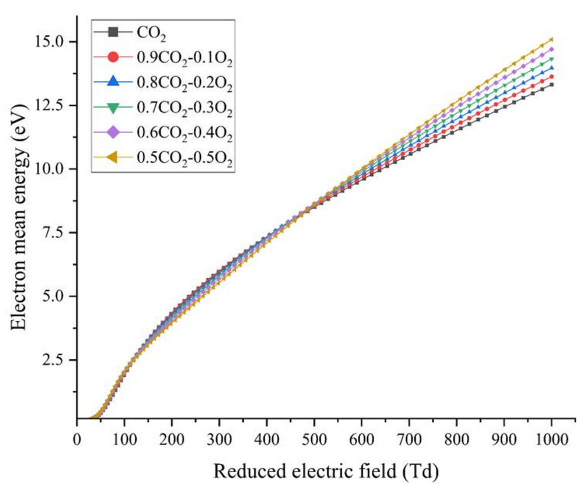

Figure 4.1: Relationship between reduced electric field (E/N) and electron mean energy (eV) with different ratios of CO_2 and O_2

4.1.2 Diffusion coefficient and reduced electric field

The **Figure 4.2** depicts the relationship graph of the diffusion coefficient multiplied by the gas number density and the reduced electric field of a CO_2/O_2 mixture at 300 K. According to the graph, the diffusion coefficient is increasing in relation to the reduced electric field (E/N). The upward trend indicates that increasing the O_2 content of the CO_2/O_2 mixture increases the mean free path of electrons. This will increase the electron avalanche process and as a result the streamer formation will increase [37]. On the other hand, by increasing the amount of CO_2 in the gas mixture the diffusion coefficient will decrease. The higher atomic mass of CO_2 makes it more heavier gas as compared with O_2. Hence, decreasing the CO_2 concentration will increase the diffusion coefficient of the gas mixture.

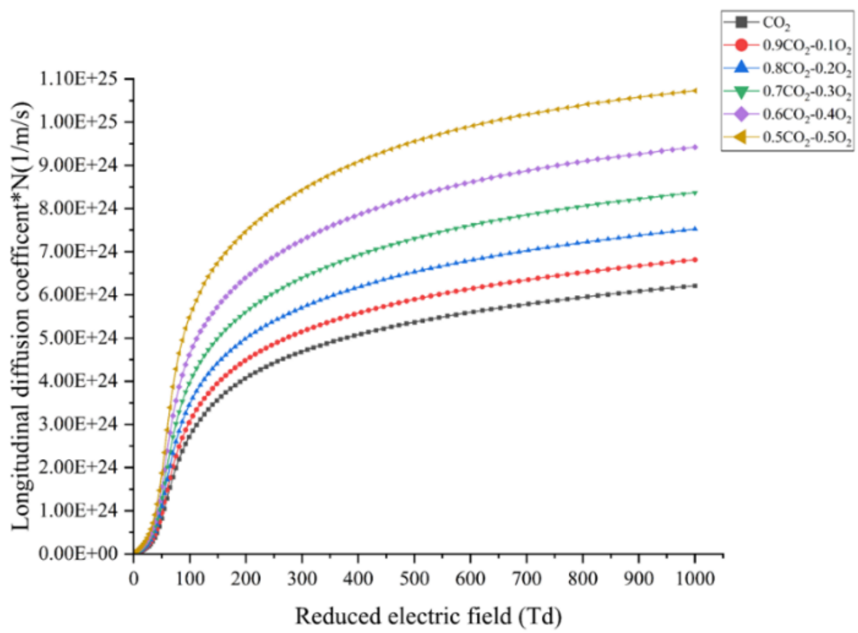

Figure 4.2: Longitudinal diffusion coefficient with different CO_2 and O_2 ratios

4.1.3 Electron mobility and reduced electric field

The graph of electron mobility and the reduced electric field has shown in the **Figure 4.3**. From the graph, the electron mobility shows the same trend as in case of longitudinal diffusion of the gas. At low reduced electric below 100 Td the electron mobility of a gas mixture shows the upward trend. At lower energy levels the electrons experiences less collision reactions with other gas molecules, and due to this reason their mobility increases [38]. At higher energy levels, the electron mobility increases. The electrons gain more energy at higher energy levels and hence their average speed will increase. The gain in speed will also tend to increase the average collisions and due to this reason, the electron mobility reduces at higher energy levels. The ionization collision cross section of CO_2 is lower than O_2 at a specific value of energy and also CO_2 is heavier than O_2 [39]. Hence, by increasing the O_2 ratio the electron mobility value decreases with an increase in the reduced electric field value.

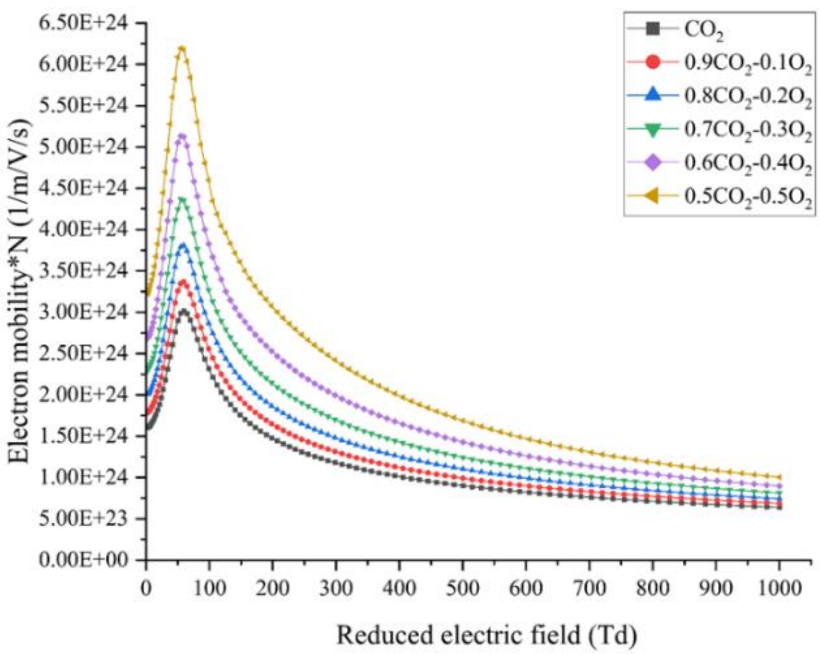

Figure 4.3: Electron mobility and reduced electric field

4.1.4 *Reduced ionization, attachment coefficient and reduced electric field*

The **Figure 4.4** shows the reduced ionization coefficient of the gas mixture and the reduced electric field. The reduced ionization coefficient (/N) of a gas mixture is primarily determined by the gas mixture's composition. At a given energy, O2 has a greater ionization cross section than CO2. [39]. Also, the first ionization energy of O_2 is also lower than that of CO_2 [34]. The higher the gas ionization collision cross section value, the greater the probability the ionization process. At higher energy levels, electrons gain more energy, making the attachment reaction more difficult to occur. As a result, streamer discharge will easy to occur. According to figure 6, the higher the amount of CO_2 in the gas mixture, the lower the ionization coefficient of the gas mixture. The ionization in a gas mixture can be reduced with the help of electronegative gas. The value of electronegative difference of C=O band in CO_2 gas is 1 which is greater than in O=O molecule that is 0. Therefore, the presence of C=O bond in CO_2 will be responsible for the controlling the ionization reaction in CO_2/O_2 gas mixture [40].

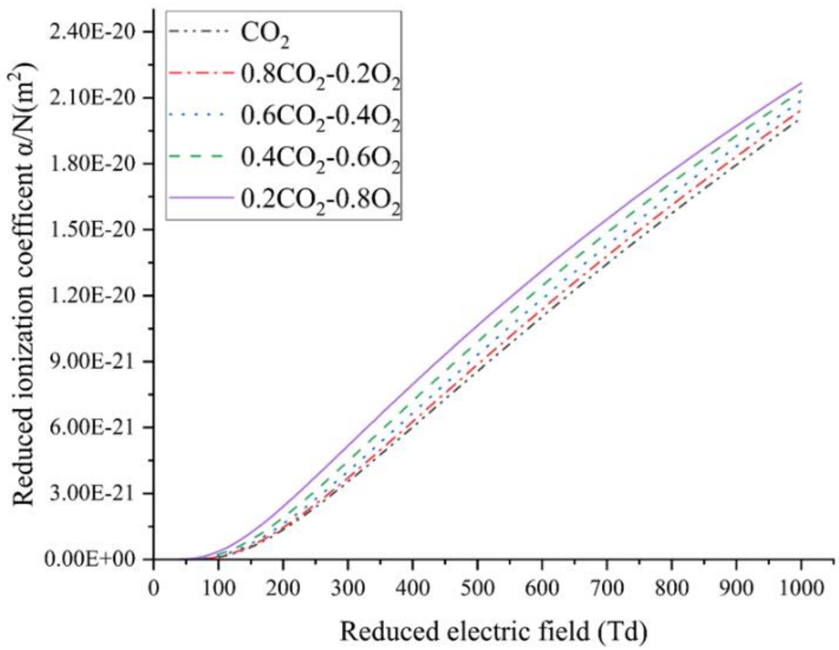

Figure 4.4: Relationship between ionization coefficient and reduced electric field (Td)

The graph between the reduced attachment coefficient and the reduced electric field has shown in the **Figure 4.5**. The graph tells about the behaviour of the CO_2/O_2 under different ratios. From the graph the attachment increases as the CO_2 ratio increases. The increase in the attachment coefficient is due to the C=O bond in CO_2 that prevents the gas mixture from ionization [40]. Also, as CO_2 has lower ionization collision section than O_2 this makes the CO_2 to act as more insulating gas as compared to O_2. Also, from the **Table 3.1**, the ionization energy of CO_2 is higher than O_2 [34]. The CO_2 will take more amount of energy than O_2 for the first ionization reaction. Hence, by increasing the amount CO_2 in a gas mixture the ionization coefficient decrease whereas attachment coefficient increases which improves the insulation behaviour of the gas mixture.

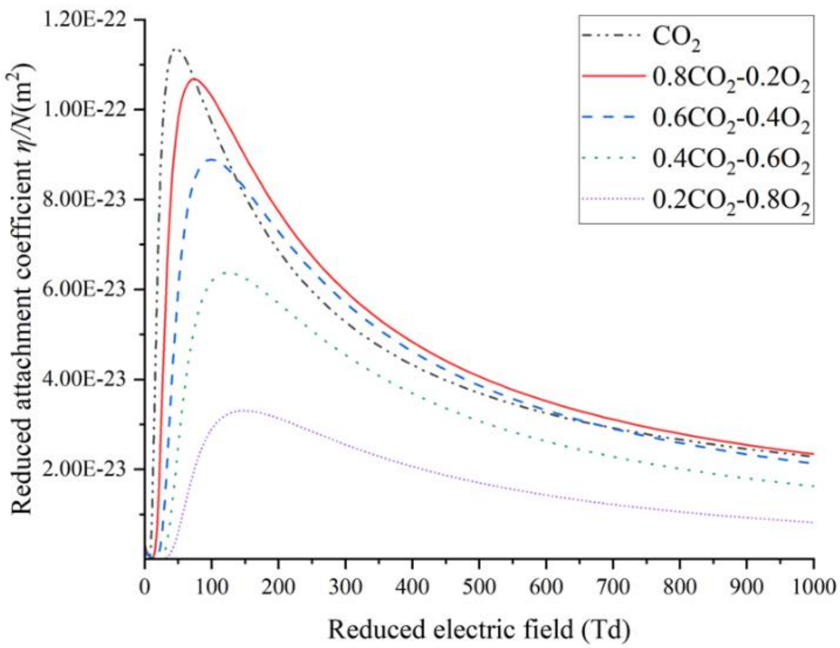

Figure 4.5: Relationship between attachment coefficient and reduced electric field (Td)

4.1.5 Electron energy distribution function and electron energy

The **Figure 4.6** shows the graph between the electron energy distribution function (EEDF) and the electron energy. The results are obtained at 300 K gas temperature and at 400 Td. As the collision cross section of O_2 is more than the CO_2 at a specific energy level, and hence more area is available for ionization reaction [39]. The electron energy will tend to increase in this case. The electron energy decreases by increasing the amount of CO_2 gas in a CO_2/O_2 gas mixture [41]. The attachment reaction mechanism of CO_2 tends to reduce the ionization collision and hence the electron energy of a gas mixture reduces. On the other hand, figure 9 shows the graph of EEDF and the electron energy at different reduced electric fields and a gas mixture of 80%CO_2-20%O_2. From the **Figure 4.7**, it is clear that by increasing the reduced electric field the electron energy will increase. The ionization process in a gas mixture is depend on the value of electron energy [9]. Hence by controlling the electron energy value the ionization process can be controlled. Once the ionization process is controlled the attachment process will dominate and the streamer require more time to form.

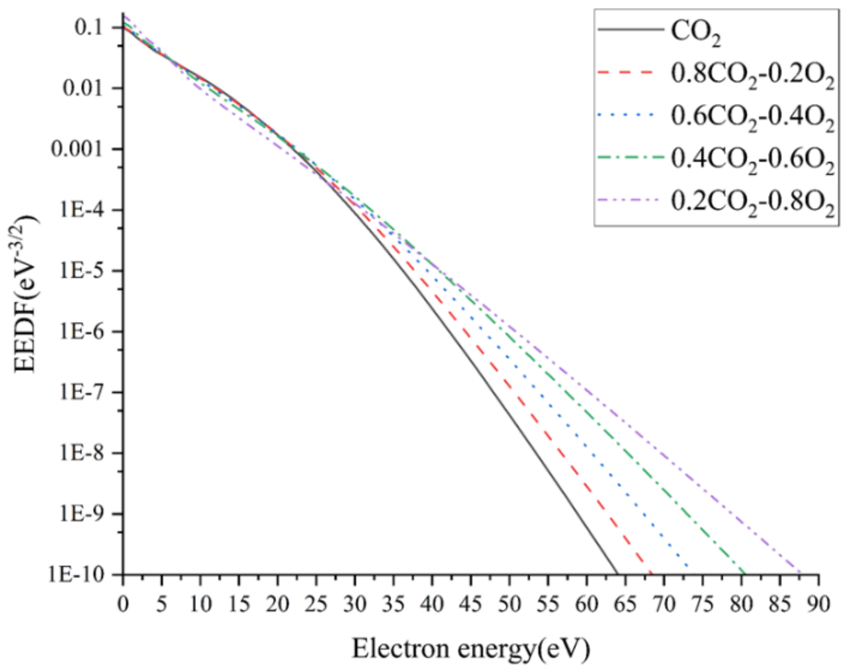

Figure 4.6: EEDF trend under different ratios

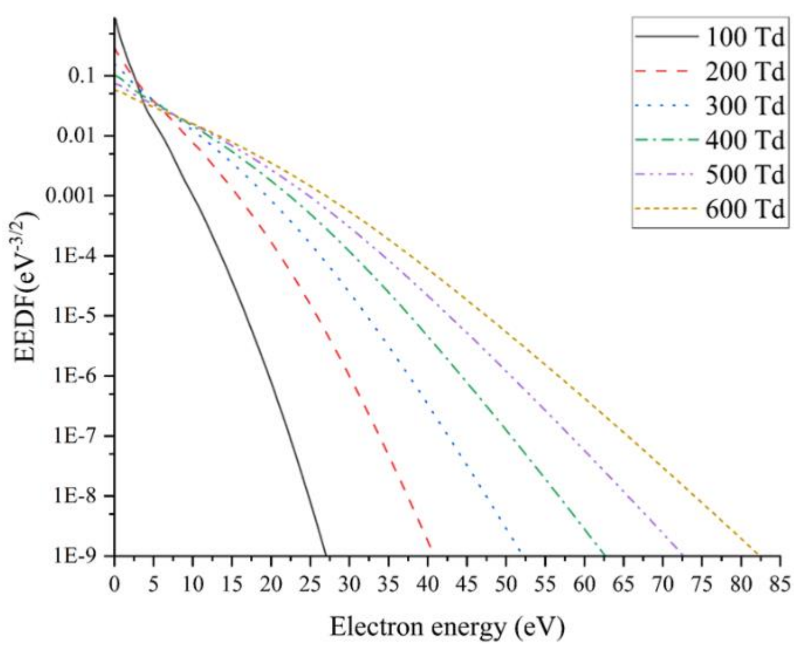

Figure 4.7: EEDF trend of 80% CO_2-20% O_2 under different E/N values

4.2 Simulation results

4.2.1 Effect of concentration ratio

The **Figure 4.8** below depicts the electron density of CO_2/O_2 under various gas mixture ratios. The different gas mixture ratios are 70% CO_2-30% O_2, 80% CO_2-20% O_2, and 90% CO_2-10% O_2. The simulation is performed under 300 K temperature, 1 bar pressure, -12 kV, and 12 kV of applied voltage. From **Figure 4.8**, the electron density increases as the concentration of CO_2 reduces and the O_2 increases. The attachment collision reaction of CO_2 becomes weak, and as a result, the ionization collision reaction becomes strong due to higher electron density. The streamer discharge will increase because of an increase in the ionization collision reaction. The streamer discharge will reach the ground electrode in a shorter time. Also, from **Table 3.1**, the ionization energy of O_2 is lower than CO_2, which makes O_2 to ionize more easily than CO_2 [34]. By increasing the O_2 concentration ratio, the ionization coefficient increases, and the attachment coefficient decreases. Therefore, the streamer discharge will enhance as the O_2 concentration ratio increases. Hence, reducing the CO_2 concentration increases the electron density, and the streamer discharge becomes prominent [40]. The complete discharge will occur in a gas mixture when the streamer reaches the ground electrode [42]. In addition, the number of different collision reactions undergo during the streamer initiation and the electron avalanche formation. These include attachment, ionization, excitation, and elastic [6, 9]. 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 [6]. Similarly, the attachment reaction reduces the generated electrons. As the applied potential is effective to ionize the gas mixture, the ionization coefficient is higher than the attachment coefficient $(\alpha\text{-}\eta) > 0$, and the streamer discharge process begins to start [11].

Similarly, the gas mixture will oppose the streamer discharge to initiate by increasing the CO_2 concentration. By increasing the CO_2 concentration ratio, the streamer discharge decreases as well as the electron number density. As the ionization energy (IE) increases, the value of σ (collision cross section) value in O_2 is higher than CO_2. This indicates the lower stability and higher reactivity of O_2 molecules than CO_2 molecules [39]. The simulation results indicate that the electron density in the negative streamer discharges is more than in the positive streamer discharges [34]. In a negative streamer discharge, electrons are responsible for initiating the discharge. Due to their lower mass than positive ions, electrons have a higher velocity in a gas mixture. Additionally, in a gas mixture, the negative streamer discharge propagates in the opposite direction of the electric field and the head contains majority of electrons [23]. On the other hand, propagation in a positive streamer discharge is along the electric field direction, and positive ions are concentrated at the streamer head [6, 43].

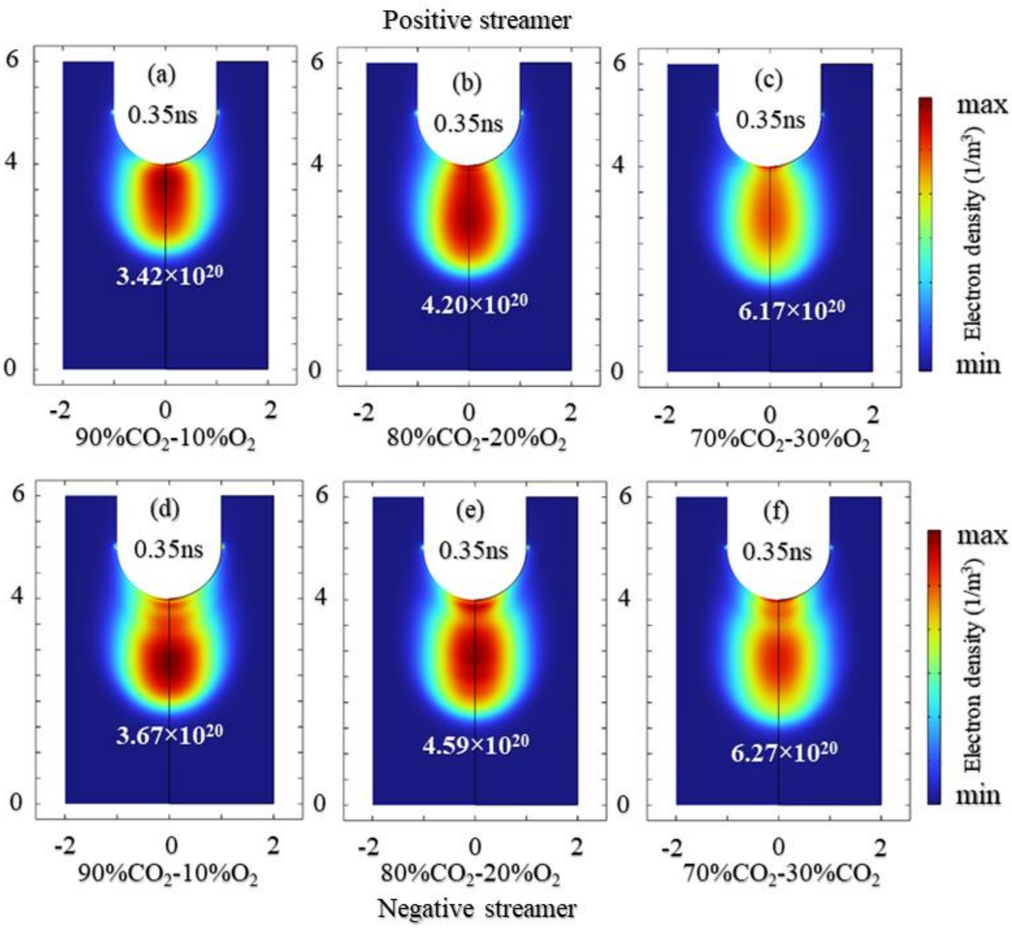

Figure 4.8: Electron density ($1/m^3$) under different gas concentration ratios

The **Figure 4.9** depicts the electric field behavior in a CO_2/O_2 gas mixture across various mixture ratios. The observed electric field behavior is similar to the electron density in the CO_2/O_2 gas mixture. When the O_2 ratio in the mixture increases, the electric field correspondingly increases. This rise in the electric field is due to the increase in electron density, which subsequently leads to enhanced secondary electron emission. The enhancement of secondary electron emission disturbs the main electric field, causing it to increase under different mixture ratios [22, 26]. The positive streamer generates a weaker electric field when compare to the negative streamer. During the streamer formation, the electric field increases proportionally with the electron density. As depicted in figure 2, the electron density of a positive streamer is lower than that of a negative streamer. This difference in electron density results in a lower electric field associated with a positive streamer [27].

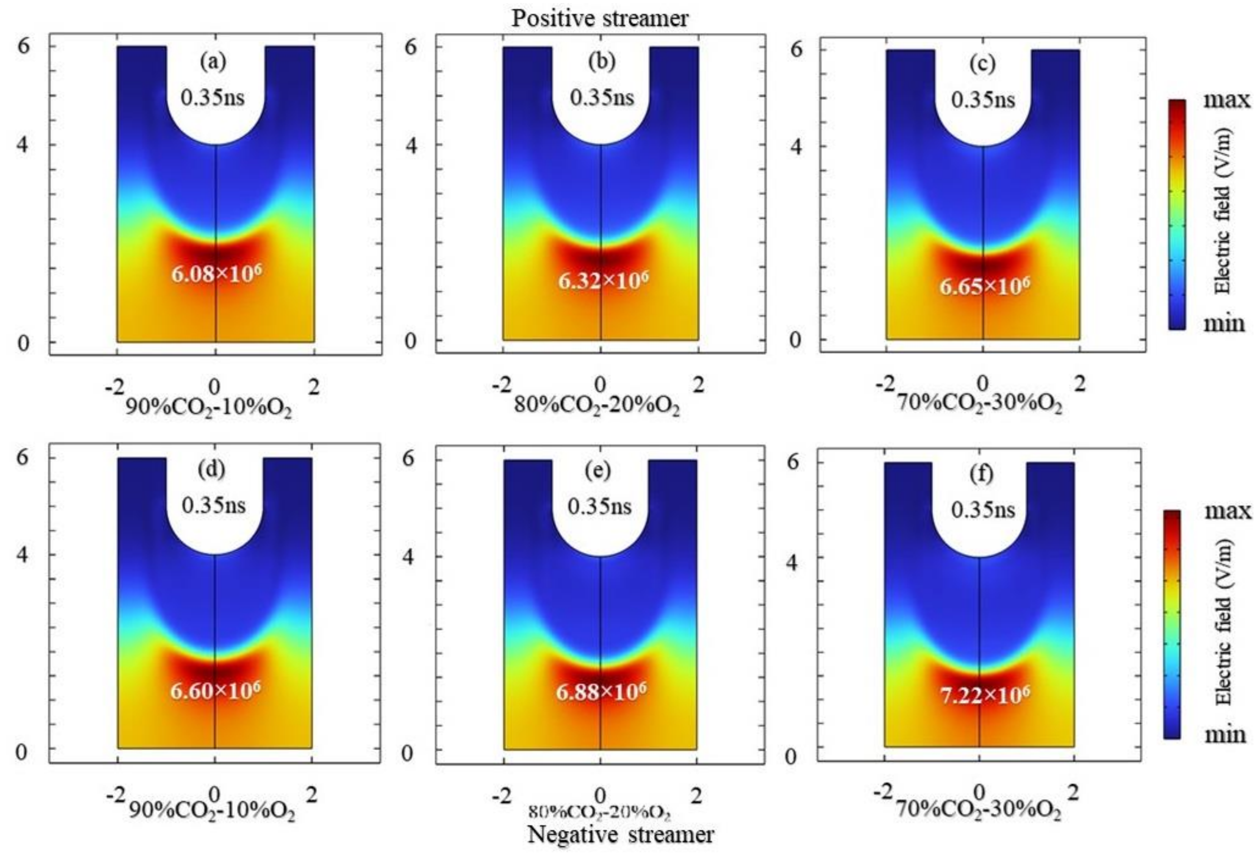

Figure 4.9: Electric field (V/m) under different concentration ratios

The streamer velocity under different gas mixtures has shown in the **Figure 4.10** below. The streamer velocity graph shows that streamer velocity depends on the gas concentration ratio. As from the above figure 2, the electron density will also enhance by increasing the O_2 concentration ratio. Due to this reason, the respective streamer velocity will also increase due to the emission of secondary electrons. Similarly, the negative streamer velocity has a higher value than the positive streamer velocity. In a negative streamer, electron drift acts in the direction of the propagation, but in a positive streamer, electron drift acts against the streamer propagation. This makes the propagation velocity of the negative streamer higher than the positive streamer in a gas mixture [44].

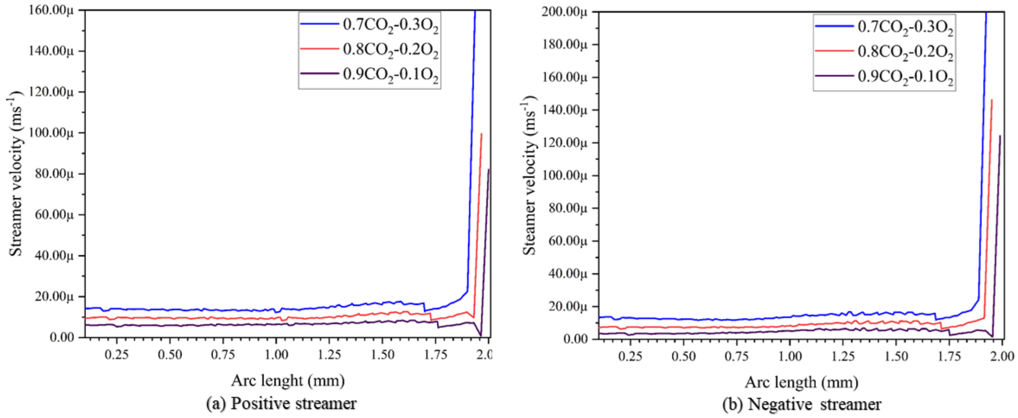

Figure 4.10: Streamer velocity (ms^{-1}) under different concentration ratios

The streamer propagation over time has shown in **Figure 4.11** below. The simulation has carried out in 80%CO_2-20%O_2 mixture ratio, ±12 kV applied voltage, and by keeping all the simulation conditions same. The figure clearly demonstrates that the electron density is initially low but gradually increases with time. This initial rise in electron density is attributed to the growth in the Townsend first ionization coefficient, as given in equation 11. The increase in the Townsend coefficient further enhances the electron density, leading to the propagation along the z-axis [33, 45]. It has observed from simulation results that the electron density in the negative streamer is higher than in the positive streamer. As the negative streamer moves against the electric field direction and in the same direction as electron drift. Hence, the streamer head is equipped with electrons. These electrons intensify the localized electric field at the streamer head, which increases the electron density as the streamer discharge propagates towards the ground electrode [27].

Similarly, the propagation direction of the positive streamer is towards the electric field, with positive ions concentrated at its head. Positive ions in a gas mixture move slowly than the electrons, creating a lower electric field enhancement and lower electron density in a gas mixture [27]. Hence, the secondary electron emission is less efficient in positive streamer discharges than in negative streamer discharges. The secondary electron emission in a gas mixture occurs due to the Townsend ionization, and this emission will convert into an avalanche process. The avalanche process causes the breakdown of a gas mixture. The positive streamer electron density at 0.35 ns time is 4.20×10^{20}, and the negative streamer electron density at 0.35 ns time is 4.59×10^{20} respectively.

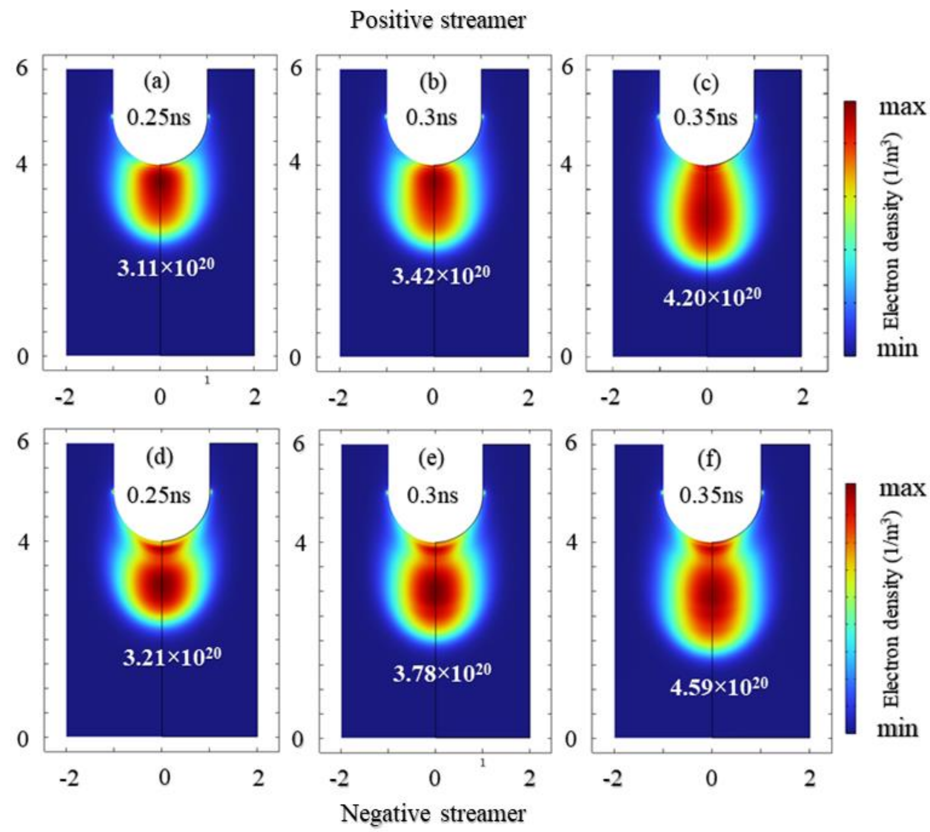

Figure 4.11: Electron density ($1/m^3$) under different time spans.

The **Figure 4.12** illustrates the electric field distribution of a CO_2/O_2 mixture over different time intervals. The electric field has shown for three specific time spans: 0.25 ns, 0.3 ns, and 0.35 ns. The electric field also increases as the discharge time increases. This is due to the increase of the electron density over time, which enhances the corresponding electric field. Consequently, the localized electric field becomes stronger as the streamer moves along its path. It has also observed from the below figure that the electric field in the positive streamer is low as compared with the negative streamer. The reason is obvious in negative streamer, the direction of propagation is along the electron drift and this creates the high-localized electric field than in a positive streamer [46]. The positive streamer electric field at 0.35 ns time is 6.32×10^{20} whereas the negative streamer electric field at 0.35 ns time is 6.88×10^{20} as shown in **Figure 4.12**.

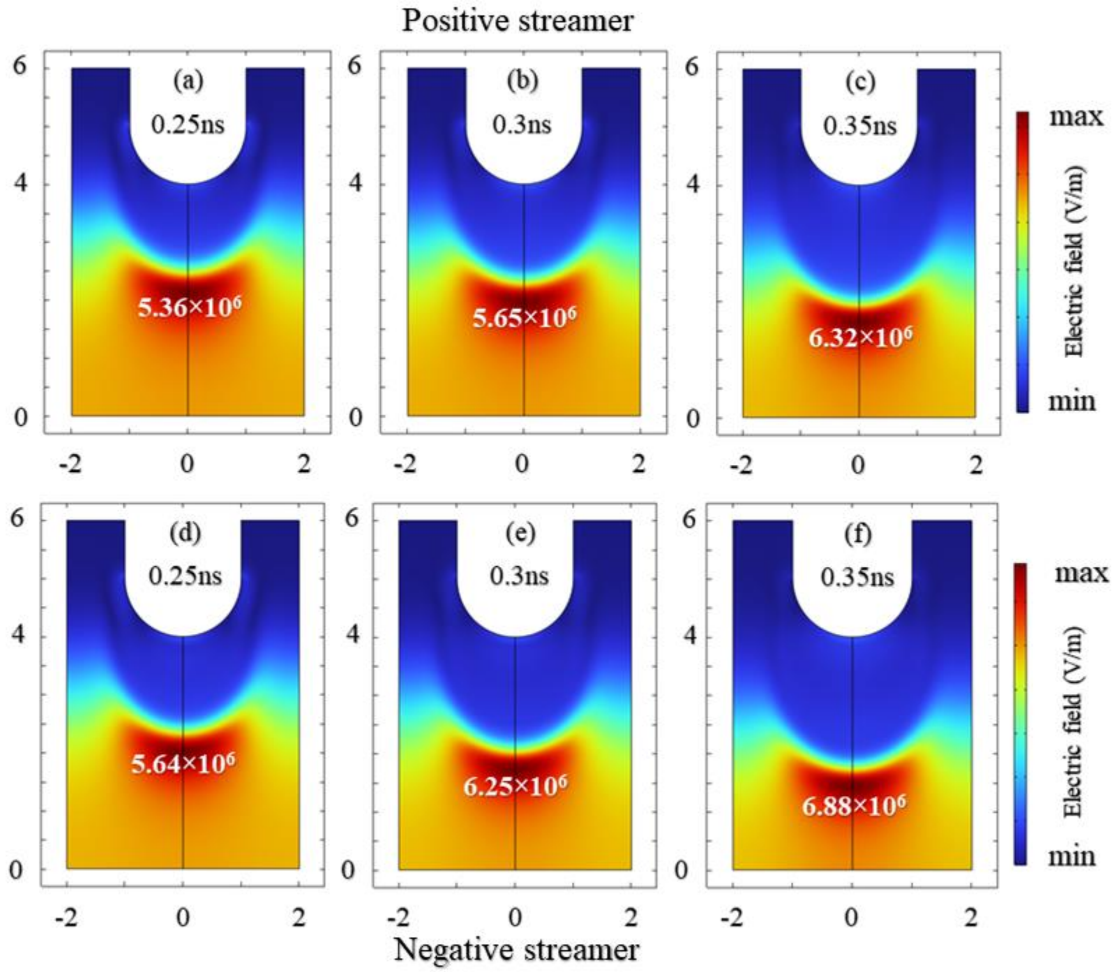

Figure 4.12: Electric field (V/m) under different time span.

Similarly, the streamer velocity of the CO_2/O_2 mixture under different time spans has depicted in **Figure 4.13**. From the figure below, the streamer velocity increases with a passage of time. The streamer velocity in a negative streamer is greater than in a positive streamer. As discussed above, the negative streamer propagates along the electron drift, and this creates the high-localized electric charges along the electrode surface. On the other hand, the positive streamer propagates in the opposite direction of the electron drift. Due to this reason, the localized electric field along the electrode surface is difficult to establish. Therefore, the positive streamer has a low propagation velocity as compared with the negative streamer under the influence of the simulation time. The positive streamer velocity at 0.35 ns is approximately 90 μms^{-1}, whereas in the negative streamer the velocity is 140 μms^{-1}.

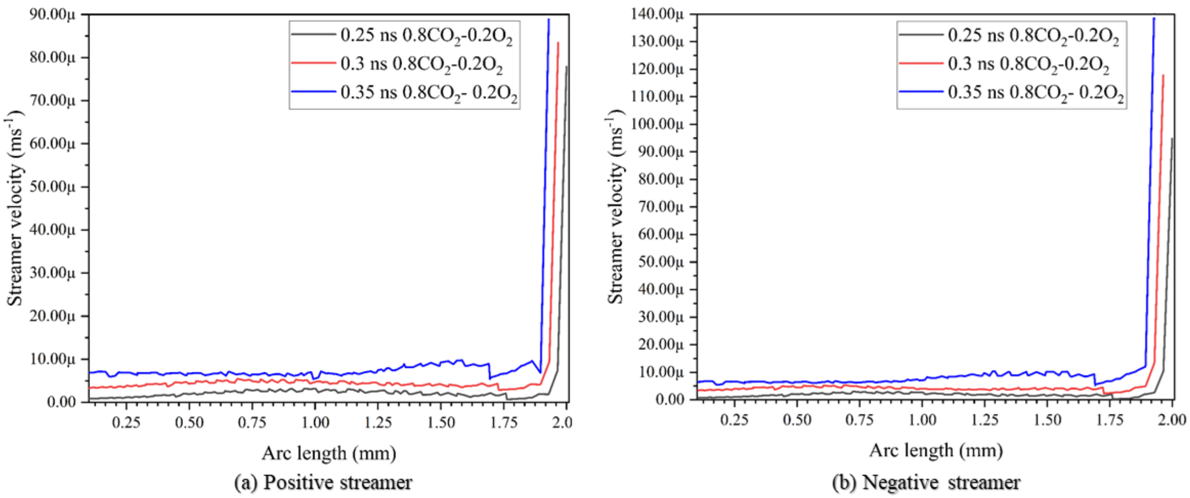

Figure 4.13: Streamer velocity (ms^{-1}) under different time.

4.2.1 Effect of applied voltage

The **Figure 4.14** below illustrates the streamer discharge in a CO_2/O_2 gas mixture under different voltage levels. For the study, a concentration ratio of 80% CO_2 and 20% O_2 has selected as the research subject, while all other simulation conditions are remain constant. As shown in **Figure 4.14**, increasing the applied voltage results in an increase in electron density. This is because, as the voltage rises, the kinetic energy of electrons increases, leading to a higher electron collision rate. Consequently, the streamer discharge propagates more rapidly, enhancing the ionization of the gas mixture [47]. Thus, by increasing the applied voltage, the ionization collision reaction becomes more dominant than the attachment collision reaction, resulting in a shorter breakdown time for the gas mixture. Specifically, the electron density increases from 1.97×10^{20} to 4.59×10^{20} when the voltage rises from -8 kV to -12 kV at 0.35 ns, as depicted in Figure 5. A similar increasing trend in electron density has observed for the positive streamer as well, with electron density rising from 1.73×10^{20} to 4.20×10^{20} as the applied voltage has increased from 8 kV to 12 kV.

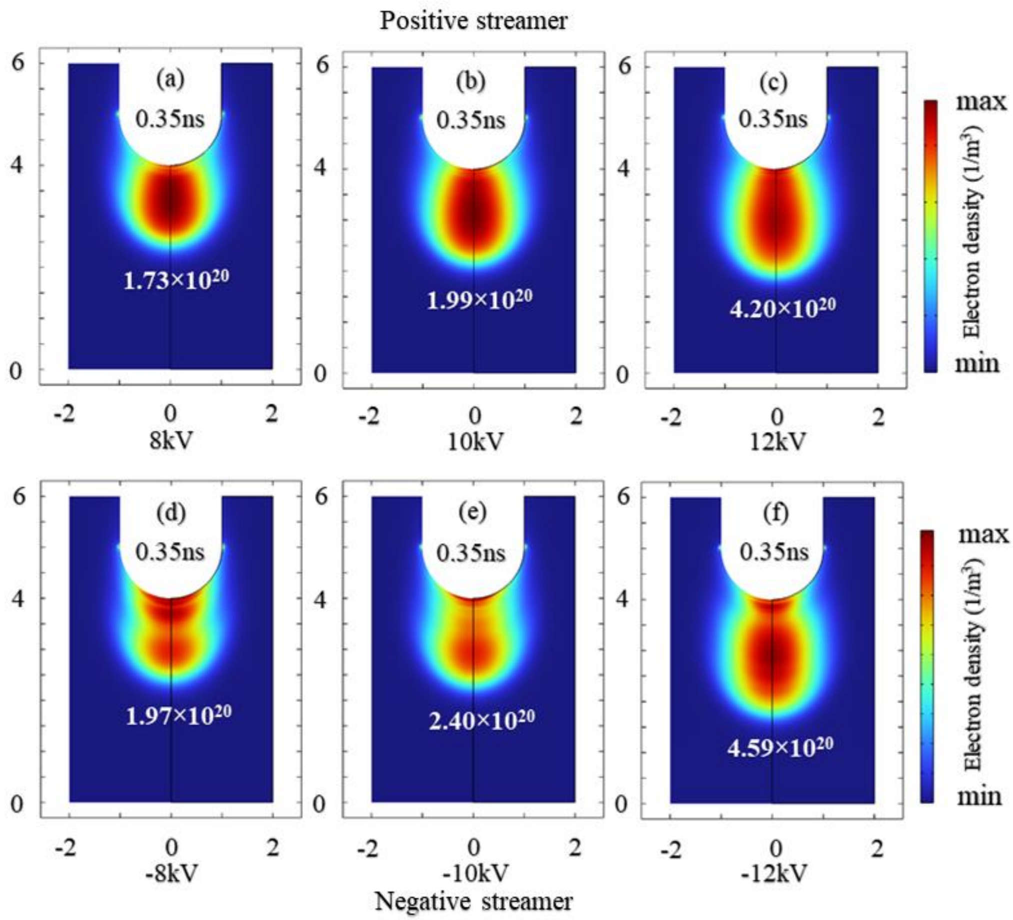

Figure 4.14: Electron density (1/m3) at different voltage levels.

Figure 4.15 shows the electric field behaviour under different voltage levels. The electric field increases in both streamer discharges as the voltage rises. This is due to the increase in ionization collisions within the gas mixture as the applied potential rises. As the ionization collisions become more frequent, the electric field increases, which enhances the secondary ionization collisions. Specifically, in the positive streamer, the electric field increases from 3.58×10^6 to 6.32×10^6 when the voltage has raised from 8 kV to 12 kV. In contrast, in the negative streamer, the electric field rises from 3.77×10^6 to 6.88×10^6 when the voltage has increased from -8 kV to -12 kV.

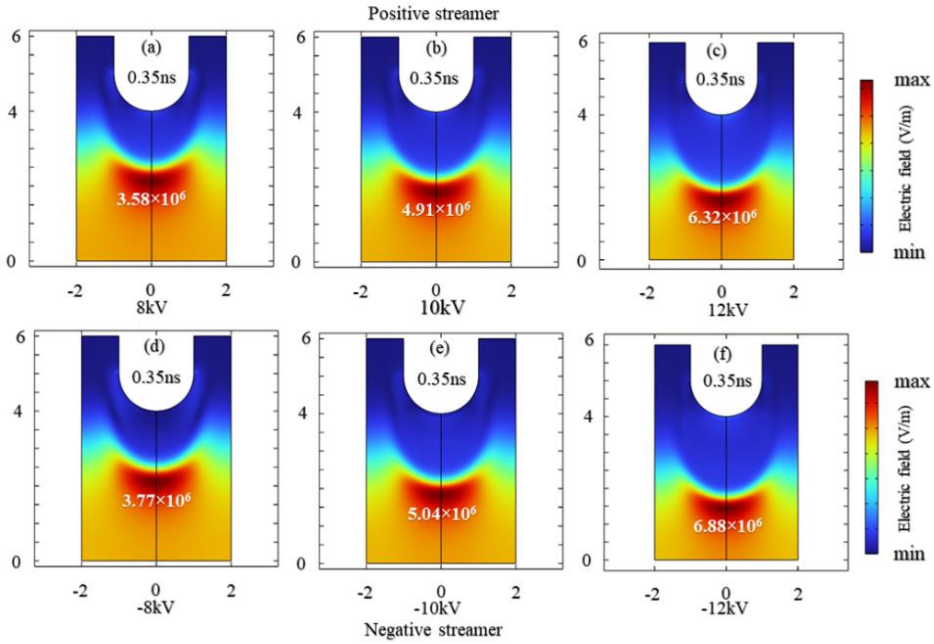

Figure 4.15: Electric field (V/m) under different voltage levels.

The **Figure 4.16** below illustrates the streamer velocity at various voltage levels. As the voltage increases, the streamer velocity increases as well. This occurs because a higher voltage enhances the ionization process of a gas mixture and increases the secondary electron emission. These electrons accelerate the streamer velocity. The figure also indicates that the negative streamer velocity is greater as compared to the positive streamer. The propagation direction of the negative streamer is towards the electron drift, whereas the positive streamer moves against the electron drift. As a result, under the same simulation conditions, the positive streamer velocity is lower as compared to the negative streamer. The positive streamer velocity at 12 kV is 90 μms^{-1} and the negative streamer velocity at -12 kV is 140 μms^{-1}.

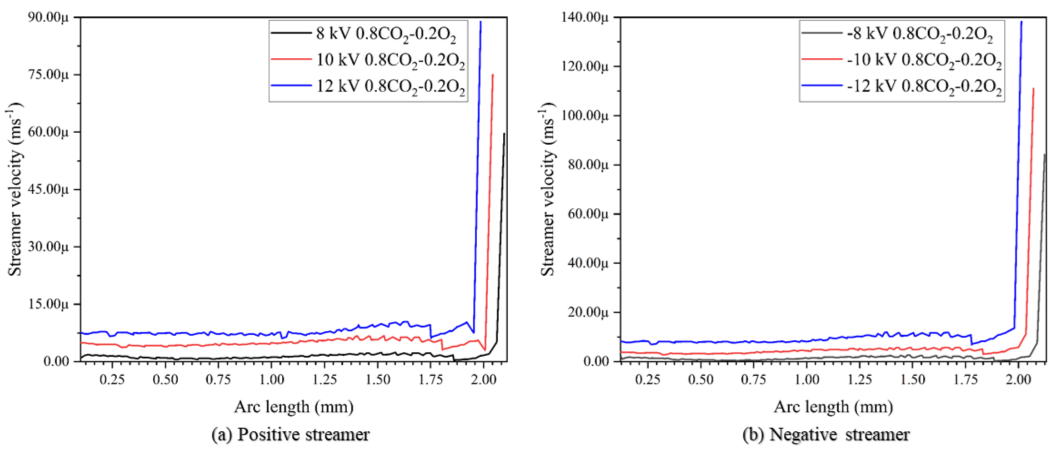

Figure 4.16: Streamer velocity under different voltage levels.

4.2.2 *Effect of gas pressure*

Similarly, when the gas mixture pressure increases, the electron density decreases. As the gas pressure rises, gas molecules become close to each other, creating a lower mean free path, which makes ionization collision reactions more difficult to occur. With higher pressure, electron density decreases, and the discharge time increases accordingly [6, 31]. This reduction in ionization collisions occurs because the proximity of gas molecules limits the occurrence of such reactions. The means free path of molecules reduces by increasing the gas pressure and electron diffusion decreases. The reduction in electron diffusion leads to fewer collisions in the gas mixture, thereby diminishing the streamer discharge [31]. Equations 1, 2, and 11 provide the necessary calculations for determining the electron density of the gas mixture. Figure 11 also demonstrates the electron density for both discharges across various pressure levels. As depicted in the figure, the rate of decrease in electron density for the positive streamer is more pronounced than that observed in the negative streamer. This phenomenon happens because of the lower initial electron density in the positive streamer. Additionally, as pressure increases, the electron density in the positive streamer decreases rapidly when compare with the negative streamer. The simulation result shows the clear impact of increasing pressure on the streamer discharge in a gas mixture.

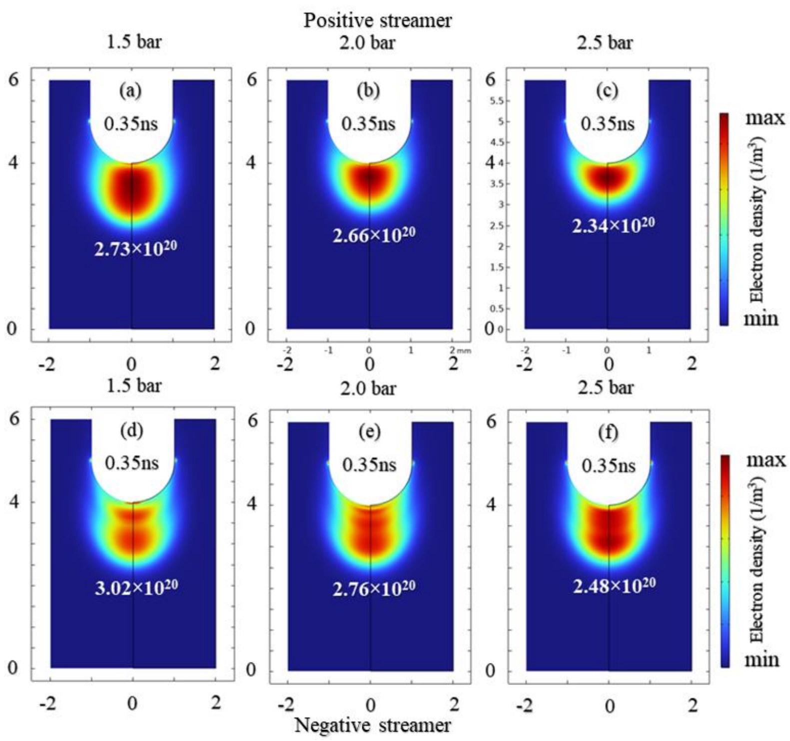

Figure 4.17: Electron density ($1/m^3$) under different pressures.

The electric field under different pressure levels has depicted in **Figure 4.18** respectively. With increasing the gas pressure, the electron density decreases, and due to this the respective electric field also decreases. The gas molecules and ions are close to each other causing the electric field to decrease as the gas pressure enhances. Therefore, the streamer propagation is difficult to occur, as the gas molecules are close to each other. The lower propagation causes the electric field to decrease. The positive streamer electric field decreases from 5.25×10^6 to 4.51×10^6 and the negative streamer electric field decreases from 5.42×10^6 to 4.70×10^6 as the pressure increase from 1.5 bar to 2.5 bar respectively.

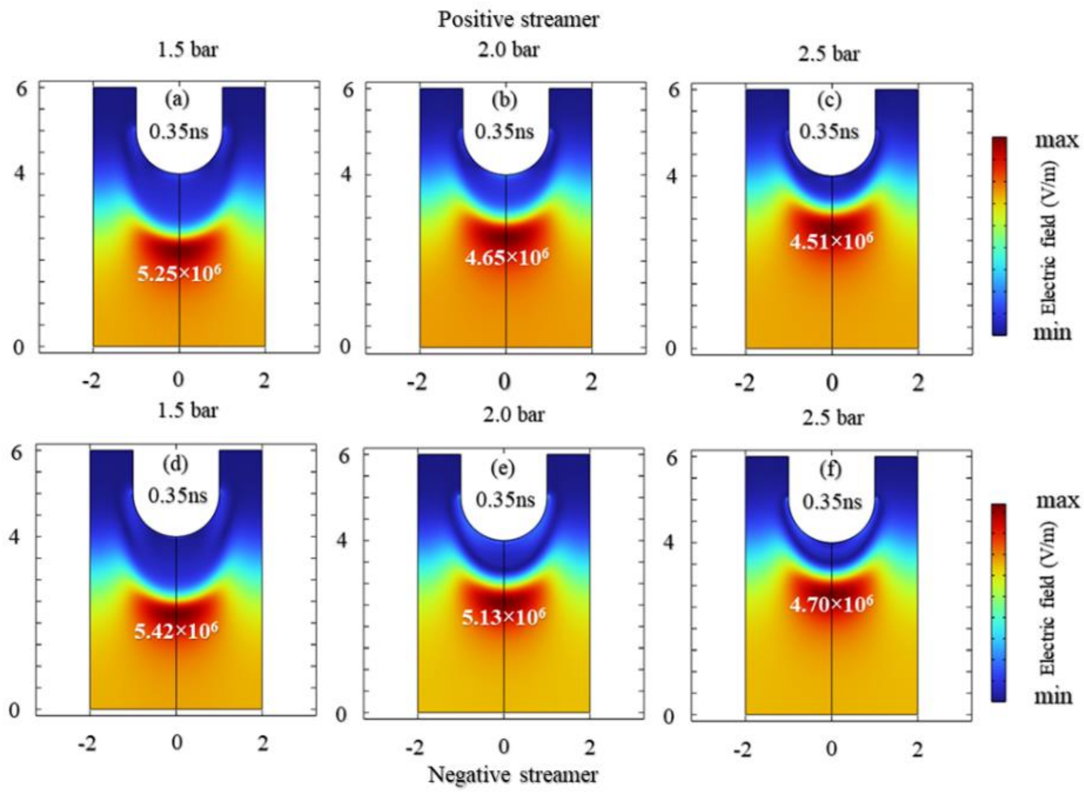

Figure 4.18: Electric field (V/m) under different pressures.

The streamer velocity graph under different pressure levels has depicted in **Figure 4.19** below. By increasing the gas pressure, the gas molecules become compact, and streamer velocity decreases. The streamer initiation becomes difficult, and hence streamer velocity reduces. Similarly, the negative streamer velocity is higher than the positive streamer velocity. The high negative streamer velocity corresponds to the high electron density as compared with the positive streamer. The positive streamer velocity at 2.5 bar is 70 μms^{-1} and the negative streamer velocity at 2.5 bar is 80 μms^{-1}.

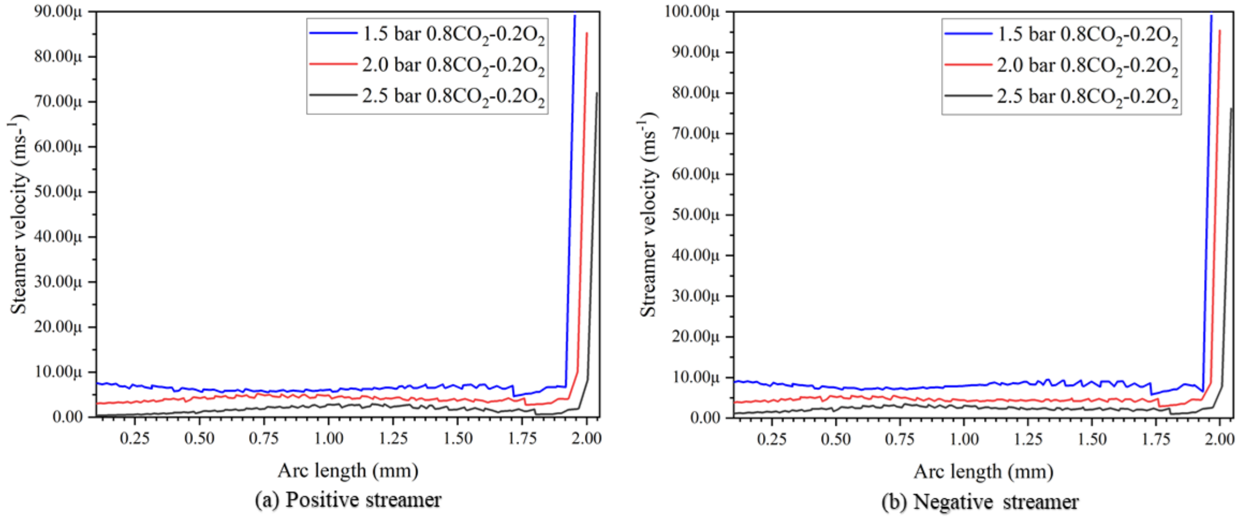

Figure 4.19: Streamer velocity (ms^{-1}) under different pressures.

4.2.3 Effect of electrode gap distance

The electrode distance influence on the streamer development has shown in **Figure 4.20**. The electrode distances of 4mm, 4.5mm, and 5mm have selected for the study by keeping the simulation conditions unchanged. The simulation results indicate that increasing the distance between the electrodes reduces the electron density, causing the streamer discharge to take more time to reach from the rod to the plane electrode. By increasing the electrode distance, the streamer discharge will undergo a longer path to develop, which decreases the electron density [48]. The streamer discharge initiation will become faster by increasing the electric potential, resulting in a breakdown of the gas mixture in a shorter time. Hence, by increasing the electrode distance, the electron density will decrease at a specific time and reduce the streamer discharge in a gas mixture. Furthermore, **Figure 4.20** also shows the positive and negative streamer electron densities. The electron density for the negative streamer has a higher value than the positive streamer. The high electron density value of the negative streamer is due to the high secondary electron emission. The electron density for the positive streamer at 4mm of electrode distance is 4.20×10^{20}, which decreases to 2.80×10^{20} at 5mm of electrode distance. Whereas electron density for the negative streamer at 4mm of electrode distance is 4.59×10^{20}, which decreases to 3.35×10^{20}.

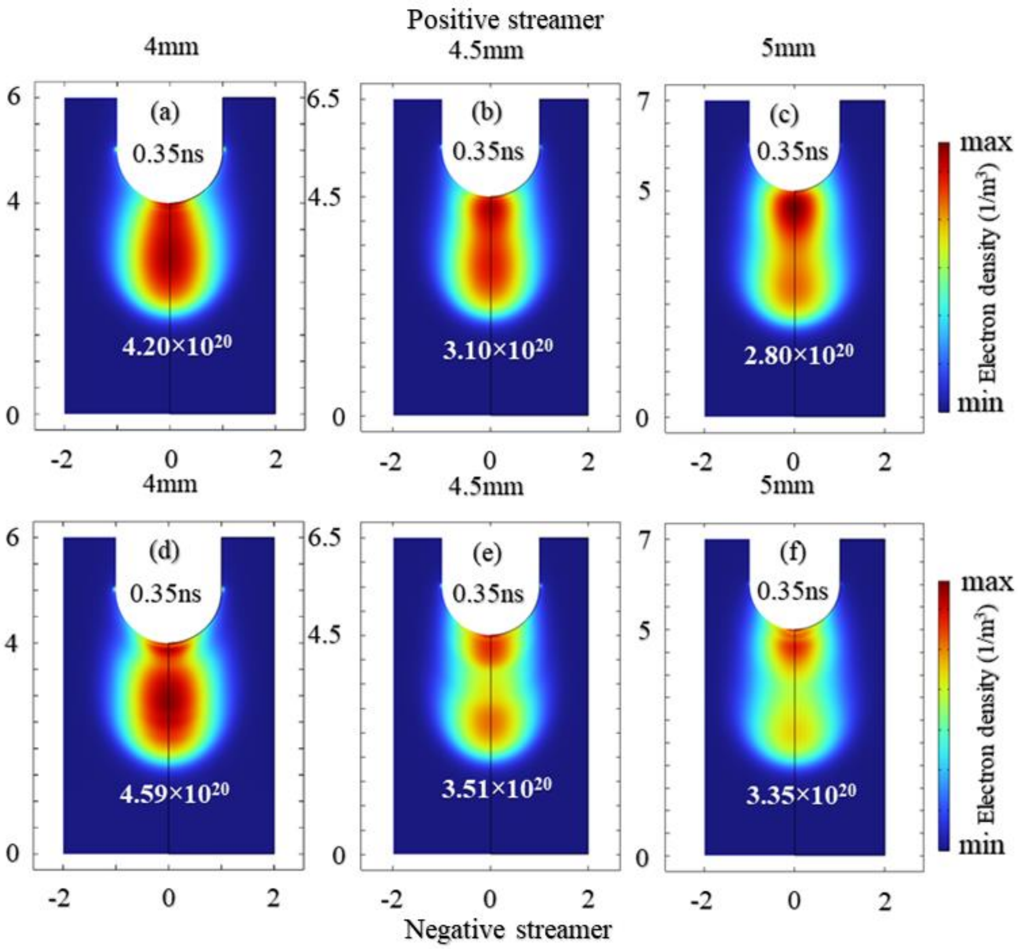

Figure 4.20: Electron density ($1/m^3$) under different electrode distances.

The electric field trend for streamer discharge of different electrode distances has depicted in **Figure 4.21**. The electric field shows the same results as electron density. The streamer discharge decreases with the increase of the electrode distance, and this causes the electric field to decrease. The positive streamer has the higher decreasing trend of the electric field than that of the negative streamer. By increasing the gap distance, the streamer discharge travels a longer distance and hence increases the discharge time. Hence, the maximum electron density decreases at a particular time. The electric field at 4mm of electrode distance is 6.32×10^6, which decreases to 5.89×10^6 at 5mm of electrode distance. Similarly, the electric field for the negative streamer at 4mm of electrode distance is 6.88×10^6, which decreases to 6.19×10^6 at 5mm of electrode distance respectively.

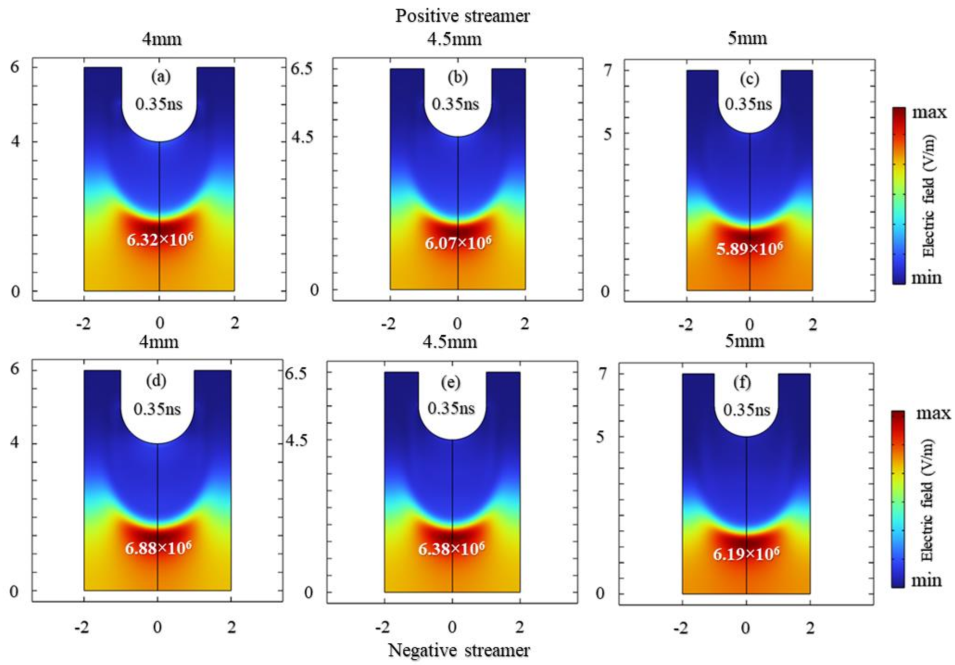

Figure 4.21: Electric field (V/m) under different electrode distances.

The streamer velocity graph for different electrode distances has shown in **Figure 4.22**. The graph shows that streamer velocity decreases as the electrode gap increases. The steamer velocity decreases because of the decrease in the electron density and the electric field. The streamer takes more time to propagate as the distance increases in the electrodes. Hence, the streamer velocity decreases as the electrode distance increases. Similarly, the streamer velocity in the negative streamer is higher when compare with the positive streamer. The positive streamer velocity at a 5 mm gap is 40 μms^{-1} and the negative streamer velocity at a 5 mm gap is 70 μms^{-1} respectively.

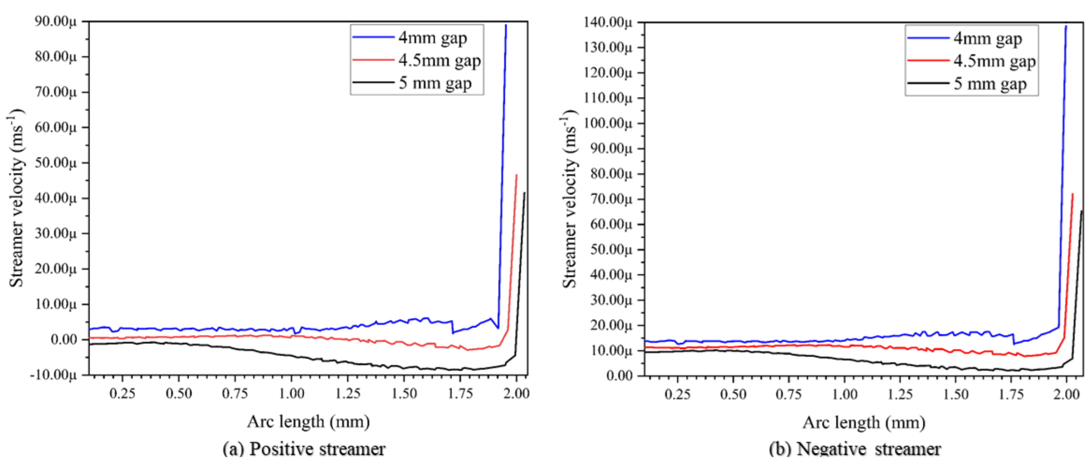

Figure 4.22: Streamer velocity (ms^{-1}) under different electrode distances.

The streamer discharge study in CO_2/O_2 with the help of an experiment was carried out by Kumar and his other co-workers. The authors carried out the experiment with the help of the 500 kV Marx generator. The authors performed the experiment based on 10% CO_2-30% O_2 mixture gas in a 0.1-1 MPa pressure range with a rod to plane and needle to plane geometry. In this experiment, they concluded that breakdown in a CO_2/O_2 based mixture is strongly dependent on the geometry structure and on the applied voltage polarity [17]. The positive polarity has a lower breakdown strength. This indicates the less propagation of streamer discharge in case of positive DC voltage. The higher availability of free electrons in the negative polarity significantly contributes in increasing the streamer propagation. When comparing the experimental findings with the simulation results, it has concluded that simulation geometry is a critical factor in streamer development. The negative streamer not only propagates more quickly but also contains a greater number of free electrons as compared to the positive streamer. Therefore, the availability of electrons in the negative streamer results in higher electron density and a stronger electric field, which is relatively lower in the positive streamer.

SUMMARY

This is the main chapter of the thesis. In this chapter, the detail results of the simulation have covered. The results have divided in two sections. In first section, the electron transport properties of CO_2/O_2 have discussed in detail. In the second section, the simulation results have discussed. By analyzing the different results, it has concluded that by increasing the O_2 concertation ratio the streamer discharge increases. Similarly, by increasing the pressure and the gap distance the streamer discharge decreases. On the other hand, applied voltage has direct effect on the streamer discharge. These results have also compared with the available literature to ensure that simulation results are true according to the literature.

CHAPTER 5: CONCLUSION

In this thesis, the streamer discharge initiation and propagation behaviour of CO_2/O_2 mixture is carried out with a help of simulation of rod to plane geometry in a two dimensional axis-symmetric space dimension along with plasma physics. The thesis is distributed in five different sections. The first section is based on the introduction of the thesis. The second chapter is the literature review of the thesis. In the third chapter, the model formation and the establishment of the reaction mechanism for the CO_2/O_2 gas mixture has completed. The Boltzmann two term approximation equation, Poisson equation and the electrostatics equations are used to study the streamer discharge behaviour in a gas mixture. After establishing the simulation model, the electron transport properties of CO_2/O_2 have calculated. The electron transport properties are obtained with the help of Bolsig+ numerical based software. The electron transport properties show that by increasing the amount of CO_2 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 CO_2/O_2 the EEDF increases with an increase of reduced electric field (Td). The kinetic energy of a gas mixture increases with the increase of reduced electric field and hence the EEDF will increase. Similarly, the decrease in the electron mean energy with an increase of CO_2 in a gas mixture is due to the attachment reaction of CO_2 that reduces the ionization reaction in a gas mixture. The longitudinal diffusion coefficient and electron mobility decreases is due to the reason that CO_2 is a heavier gas than O_2 so diffusion of the gas mixture will reduce by increasing the CO_2 content. Similarly, reduced ionization coefficient decreases as CO_2 content increases is due to the reason that CO_2 has higher ionization energy than O_2 due to this reason more energy is required to breakdown the mixture gas. The increase in the attachment reaction of CO_2/O_2 mixture is due to the reason that collision cross section of CO_2 is lower than O_2 that makes it more stable in a gas mixture.

The streamer discharge initiation and propagation of the CO_2/O_2 mixture has carried out with the simulation of the rod to plane geometry in a two-dimensional axis-symmetric space dimension along with the plasma physics domain. The Poisson equation, Gaussian approximation and Townsend first ionization coefficient have applied to study the streamer discharge behaviour in a gas mixture. The streamer discharge characteristics under different conditions have studied in detail. The effect of gas concentration ratio, gas pressure, applied voltage, time and electrode distance on the streamer initiation and propagation have examined along with the electron density, electric field and streamer velocity graphs. The following conclusion points have drawn based on the simulation results.

- The negative streamer discharge propagation is significantly higher when comparing with the positive streamer discharge. The high propagation velocity in the negative streamer is due to the stronger electric field. Furthermore, the streamer discharge in a gas mixture increases with the voltage and decreases with the increase in the gas pressure.
- The propagation direction of the negative streamer is along the electron drift, and the positive streamer propagates against the electron drift. The negative streamer head is equipped with electrons as it propagates along the electron drift, so electron density is high in the negative streamer. Similarly, the positive streamer head consists of positive ions, and due to this reason, electron density is low.
- The electron drift also influences the negative streamer velocity, but the electron drift does not influence the positive streamer. Photoionization is required to generate the extra electrons in the streamer head of the positive streamer velocity.
- The σ (collision cross section) value of O_2 is greater than CO_2 at the ionization energy. This indicates that O_2 molecules in a gas mixture have higher reactivity and lower stability. This indicates the higher streamer formation in a CO_2/O_2 gas mixture as the O_2 concentration increases in a gas mixture.
- The streamer velocity shows the same trend as the electron density and electric field in a gas mixture. Due to this reason when the electron-density or electric field changes the streamer propagation velocity will follow the same trend.
- By increasing the voltage, electrons gain more energy and the streamer propagates rapidly. Similarly, increasing the pressure in a gas mixture decreases the effective ionization collision between the atoms, resulting a decreasing in the streamer discharge. In the same way, by increasing the amount of CO_2 in a gas mixture, the ionization coefficient decreases, and due to this reason, the electron density decreases.

- The electrode gap distance also influences the streamer discharge. As the electrode length increases, the streamer discharge decreases over a specific time. A longer electrode length means the streamer discharge takes more time to reach the ground electrode. The simulation results presented in this thesis are based on ideal conditions, excluding external factors such as metal contamination particles from consideration.

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] M. F. Abbas, Y. L. He, G. Y. Sun, A. B. Sun, E. T. Eldin, and S. S. Ghoneim, "Positive Streamer Initiation in SF 6/CO 2 Based on Zener's Field Ionization," *Ieee Access,* 2023.

[3] P. Billen, B. Maes, M. Larrain, and J. Braet, "Replacing SF_6 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.

[4] 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.

[5] B. Zhang, J. Xiong, L. Chen, X. Li, and A. B. Murphy, "Fundamental physicochemical properties of SF_6-alternative gases: a review of recent progress," *Journal of Physics D: Applied Physics,* vol. 53, no. 17, p. 173001, 2020.

[6] R. Zhang, L. Wang, J. Liu, and Z. Lian, "Numerical simulation of breakdown properties and streamer development processes in SF_6/CO_2 mixed gas," *AIP Advances,* vol. 12, no. 1, p. 015003, 2022.

[7] M. Gatzsche *et al.*, "Moving towards carbon-neutral high-voltage switchgear by combining eco-efficient technologies," *CIGRE Paris session,* 2022.

[8] M. Muratovic *et al.*, "An Experimental Circuit Breaker for Benchmarking the Intrinsic Interruption Performance of SF_6 Alternative Gas Mixtures," *IEEE Transactions on Power Delivery,* 2024.

[9] 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.

[10] X. Meng, H. Mei, F. Yin, and L. Wang, "The development of the streamer discharge to flashover along the dielectric surfaces," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 30, no. 4, pp. 1733-1742, 2023.

[11] 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.

[12] Z. Wang *et al.*, "Quantitative modeling of streamer discharge branching in air," *Plasma Sources Science and Technology,* vol. 32, no. 8, p. 085007, 2023.

[13] A. A. Dubinova, "Modeling of streamer discharges near dielectrics," 2016.

[14] Z. Zhao, Z. Huang, X. Zheng, C. Li, A. Sun, and J. Li, "Evolutions of repetitively pulsed positive streamer discharge in electronegative gas mixtures at high pressure," *Plasma Sources Science and Technology,* vol. 31, no. 7, p. 075006, 2022.

[15] Y. Yang, X. Wen, L. Wang, and X. Wang, "Study on Townsend first ionization coefficient in a streamer filament of the pulsed electric discharge in water," *Physics of Plasmas,* vol. 29, no. 9, 2022.

[16] 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.

[17] 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.

[18] 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.

[19] B. Bagheri, J. Teunissen, and U. Ebert, "Simulation of positive streamers in CO_2 and in air: the role of photoionization or other electron sources," *Plasma Sources Science and Technology,* vol. 29, no. 12, p. 125021, 2020.

[20] X. Li, A. Sun, and J. Teunissen, "The effect of photoionization on positive streamers in CO_2 studied with 2D particle-in-cell simulations," *arXiv preprint arXiv:2304.01531,* 2023.

[21] R. Marskar, "A 3D kinetic Monte Carlo study of streamer discharges in CO_2," *arXiv preprint arXiv:2312.02634*, 2023.

[22] 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.

[23] 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.

[24] X. Yan, X. Zhou, Z. Li, Y. Qian, and G. Sheng, "Surface Discharge Characteristics and Numerical Simulation in C_4F_7N/CO_2 Mixture," *Applied Sciences,* vol. 13, no. 3, p. 1409, 2023.

[25] 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.

[26] 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.

[27] 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.

[28] B. Luo *et al.*, "Numerical simulation of the positive streamer propagation and chemical reactions in SF 6/N 2 mixtures under non-uniform field," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 27, no. 3, pp. 782-790, 2020.

[29] M. Leutbecher and T. Haiden, "Understanding changes of the continuous ranked probability score using a homogeneous Gaussian approximation," *Quarterly Journal of the Royal Meteorological Society,* vol. 147, no. 734, pp. 425-442, 2021.

[30] S. David Müzel, E. P. Bonhin, N. M. Guimarães, and E. S. Guidi, "Application of the finite element method in the analysis of composite materials: A review," *Polymers,* vol. 12, no. 4, p. 818, 2020.

[31] X. Ou, L. Wang, J. Liu, and X. Lin, "Numerical simulation of streamer discharge development processes with multi-component SF_6 mixed gas," *Physics of Plasmas,* vol. 27, no. 7, 2020.

[32] X. Jia, H. An, Y. Hu, and Z. Mo, "A physics-based strategy for choosing initial iterate for solving drift-diffusion equations," *Computers & Mathematics with Applications*, vol. 131, pp. 1-13, 2023.

[33] R. Talviste, P. Paris, J. Raud, T. Plank, and I. Jogi, "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.

[34] 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.

[35] L. P. Babich, "Relativistic runaway electron avalanche," *Physics-Uspekhi,* vol. 63, no. 12, p. 1188, 2020.

[36] X. Guo, X. Li, A. B. Murphy, and H. Zhao, "Calculation of thermodynamic properties and transport coefficients of CO_2–O_2–Cu mixtures," *Journal of Physics D: Applied Physics,* vol. 50, no. 34, p. 345203, 2017.

[37] A. Grishkov, Y. Korolev, and V. Shklyaev, "Monte Carlo simulation for development of electron avalanches in nitrogen at moderate and high reduced electric field," *Physics of Plasmas,* vol. 27, no. 10, 2020.

[38] F. Esposito and I. Armenise, "Reactive, inelastic, and dissociation processes in collisions of atomic oxygen with molecular nitrogen," *The Journal of Physical Chemistry A,* vol. 121, no. 33, pp. 6211-6219, 2017.

[39] 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.

[40] Y. Zhang, B. Xia, J. Ran, K. Davey, and S. Z. Qiao, "Atomic-level reactive sites for semiconductor-based photocatalytic CO_2 reduction," *Advanced Energy Materials,* vol. 10, no. 9, p. 1903879, 2020.

[41] Y. Li *et al.*, "Effect of oxygen on power frequency breakdown characteristics and decomposition properties of C5-PFK/CO 2 gas mixture," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 2, pp. 373-380, 2021.

[42] 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.

[43] 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.

[44] A. Luque, V. Ratushnaya, and U. Ebert, "Positive and negative streamers in ambient air: modelling evolution and velocities," *Journal of Physics D: Applied Physics,* vol. 41, no. 23, p. 234005, 2008.

[45] 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.

[46] 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.

[47] 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.

[48] 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.

LIST OF PUBLICATIONS

Detailed Status Information

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Title	Numerical Investigation of Positive and Negative Streamers in CO_2/O_2 Mixtures
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Special Topic	N/A
Subject Area	Basic Plasma Phenomena, Waves, Instabilities
Topical Keywords	low-temperature plasmas :, low-temperature plasmas : Atmospheric electricity, low-temperature plasmas : Low-field and Townsend discharges
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