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Positive Streamer Initiation in SF_6/CO_2 Based on Zener's Field Ionization

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ABSTRACT In this study, experiments were performed to measure the inception and breakdown voltages of SF_6/CO_2 mixed gases with varying mixing ratios at two different pressures (1 and 2 bar). Using the preliminary data obtained from the experiments, a 3D particle model was used to investigate positive streamer initiation in SF_6/CO_2 with field ionization. Field ionization using Zener's model was assumed to be similar to the electron detachment in air. The experimental results showed that at P= 1 bar, the discharge inception voltage increased for CO_2 concentrations lower than 50% and decreased for CO_2 concentrations higher than 50%. The inception voltage of 80%CO_2/20%SF_6 was close to the inception voltage of pure SF_6. A similar trend of the inception and breakdown voltages was observed at P= 2 bar. The simulation results show the evolution of the thin filaments of the streamer into three distinct stages. The streamer morphology was similar irrespective of the type and concentration of the mixed gas. Other parameters such as the electric field, electron density, and streamer length increased with increasing CO_2 concentration in SF_6 at both pressures. Zener's field ionization could be considered a primary ionization mechanism for SF_6/CO_2 in the case of very high non-uniform electric fields; however, finding the experimental validation of Zener's field ionization for electronegative gases is still a challenging task.

INDEX TERMS electric field, field ionization, gaseous breakdown, particle-in-cell, streamer discharge, SF_6, CO_2

I. INTRODUCTION

Replacing sulfur hexafluoride (SF_6) in high-voltage equipment is critical because of its high global warming potential (GWP) i.e., 23900 times higher than that of CO_2 [1]. Unfortunately, no single gas has been found with insulation performance better than that of pure SF_6 and the research focus is on investigating SF_6 mixed with gas species such as O_2, N_2, and CO_2 to partially replace SF_6 in the first phase. Although it is not an ultimate solution, this research would help in gradually removing SF_6 in high-voltage equipment until a gas or gas mixture completely replacing SF_6 is found [2].

In literature, researchers have reported the pre-breakdown and breakdown voltages of SF_6 mixed with other gases including CO_2, N_2, O_2 etc. Qiu et al. reported that a SF_6/CO_2 mixture has a higher dielectric strength than SF_6/N_2 under high electric fields in a gas-insulated transformer (GIT) [3]. This shows that SF_6/CO_2 is a promising candidate as an insulating media in equipment where electric fields are high such as GIT. N H Malik formulated the method to calculate the uniform field breakdown gradients for SF_6/N_2, SF_6/air and SF_6/CO_2 and found that the calculated values of the breakdown gradients in these mixtures are in good agreement with the experimentally measured values [4]. Y Qiu investigated the effect of electrode surface roughness on breakdown in SF_6/CO_2 and SF_6/N_2 and found that the breakdown strength of SF6/CO2 gas is slightly higher than that of SF_6/N_2 under needle-tip electrode configuration [5]. Furthermore, recently, CO_2 and its mixture with O_2, Perfluoroketones (PFK), and perfluoronitriles (PFN) have shown promising results in replacing pure SF_6 in high-voltage switchgear applications [6, 7]. However, experimental, and calculated values are useful in predicting the breakdown voltages of such mixtures but the physics behind the breakdown phenomenon is equally important to fully understand the mechanism of breakdown initiation and propagation in SF_6 mixed gases. Most previous research is of an empirical nature to investigate the dielectric strength of SF_6 alternatives by calculating the inception and breakdown voltages under different applied conditions [8, 9]. The physical mechanism underlying the actual breakdown phenomenon still lacks knowledge and requires further investigation.

The sequence of various physical processes is involved in the complete breakdown phenomena, such as free electron generation, inception cloud formation, streamer initiation and propagation, streamer-to-leader conversion, and leader propagation across the gap [10]. The quantification of these microphysical processes is difficult through experiments; therefore, simulations were performed to completely understand the breakdown process. Streamers belong to the initial phase of electric breakdown in insulating media under non-uniform field conditions and have a wide range of applications in the high-voltage industry and plasma-based technology [11, 12]. Positive streamers always develop in the direction of the applied electric field with electrons drifting in the opposite direction; therefore, an extra source of free electrons is always required, aiding them to grow across the gap. Positive streamer initiation mainly depends on several parameters such as gas composition, voltage polarity, and electric field distribution. Electron detachment for positive streamers and field emission for negative streamers have been extensively reported to explain the theory of streamer initiation in air [10]. In addition to electron detachment and field emission processes, photoionization is frequently adopted as the secondary ionization mechanism to explain the propagation of streamer discharge in air [10, 13]. Positive streamer initiation in electronegative gases is different from that in air because of the unknown source and density of negative ions prior to the streamer discharge [14]. Moreover, data on quantities such as the coefficient of recombination, coefficient of absorption coefficient, and photon absorption length are also not available and must be assumed to consider photoionization for positive streamer propagation in SF_6 [15, 16]. Similarly, it was also shown that photoionization is a two-photon process, and its probability in CO_2 and in gases with higher concentrations of CO_2 is very low [17, 18]. Therefore, it is urgently necessary to explain ionization mechanisms other than detachment and photoionization to explain the positive streamer initiation in CO_2 and its mixtures.

Most previous studies have investigated the dielectric strength of highly electronegative gases, such as SF_6 and CO_2 by calculating the inception and breakdown voltages under different applied conditions [8, 9]. However, the quantification of microphysical processes that could generate the free electrons necessary for positive streamer initiation is difficult through experiments; therefore, simulation models were developed to explain them in detail. Several studies based on particle and fluid modelling schemes have been presented to model positive streamers in air, SF_6 and CO_2 [16, 17, 19, 20]. Both fluid and particle modelling techniques have advantages and disadvantages, depending on the application. However, the particle simulation technique has the advantage of considering the stochastic behavior of streamer discharge and is therefore considered in this study. Although previous research has performed simulations to investigate streamer discharges, the physical mechanism of positive streamer initiation in strongly electronegative gases including SF_6, CO_2 still is a less-explored subject and needs further investigation. Following are the novelties and contributions made in this work.

1- A 3D model for streamer discharge in electronegative gases (SF_6/CO_2) is used which has been rarely used in the literature.
2- Field ionization is investigated as a primary ionization mechanism responsible for free electron generation in SF_6/CO_2. Usually, photoionization is considered for electron generation ahead of streamer discharges but in the case of CO_2 and mixtures with high concentration of CO_2 the probability of photoionization is very low.
3- To validate the results of simulation model, first experiments are performed to obtain the preliminary data.
4- The morphology of streamer discharge including various stages is discussed for SF_6/CO_2.

This paper is divided into five sections. Section II describes the experimental procedure and results. A 3D particle simulation model using Zener's model is presented in section III. The simulation results are presented and discussed in Section IV. Finally, the conclusions and open questions to be addressed are presented in Section V.

II. EXPERIMENTAL SETUP, PROCEDURE AND RESULTS

The experimental setup included a closed discharge chamber containing a needle-to-plane electrode geometry filled with various mixing ratios of SF_6 and CO_2, a d.c. high-voltage supply, current-limiting resistors, sampling resistors, a vacuum pump, and a digital oscilloscope, as shown in Fig. 1.

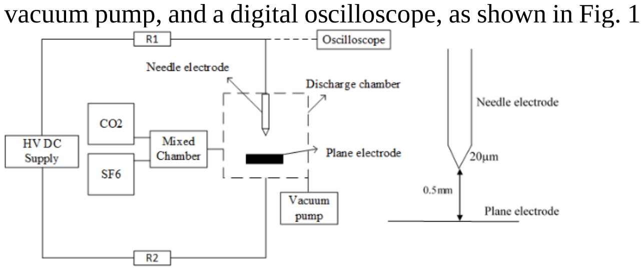

FIGURE 1. Experimental setup used to measure discharge initiation and breakdown voltage of SF_6/CO_2 mixed gas

The tip radius was 20μm and the distance from the tip to the plane was only 0.5 mm. An electron microscope was used to determine the radius of curvature of the needle tip used in the current experiment. The reason for choosing such a small gap distance with a very sharp needle electrode tip is to generate a very high non-uniform electric field in the gap, which is a prerequisite for the field Zener's field ionization process to occur. Such a small gap size and sharp needle tips have been observed in the case of protrusion faults in gas-insulated switchgears (GIS) [21]. The material of the needle electrode is tungsten-copper alloy, and stainless steel has been used for the plane electrode. The value of the current-limiting resistor (R_1) is 1 MΩ, which is used to limit the current after breakdown occurs, and R_2 is 75 Ω, which is used to ground the planar electrode. The discharge chamber was sealed and filled with different mixing ratios of SF_6/CO_2 at varying pressures (1 bar and 2 bar). An oscilloscope (Lecroy WaveSurfer 104MXs-B) with a bandwidth of 1 GHz and 10GS/s sampling rate. A quartz window was installed in the discharge chamber for optical observation of the electrical discharge.

The discharge chamber was first evacuated using a vacuum

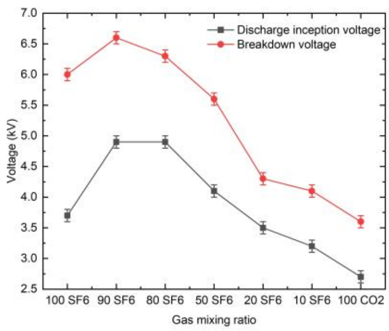

Figure 1 Discharge inception and breakdown voltage distribution of different mixing ratios of SF_6/CO_2 gas with different mixing ratios at *P*=1bar

breakdown phenomenon has been interpreted in many ways in both theory and experimentation; however, owing to the variety of determining techniques, it is still one of the least understood topics. When determining breakdown time in dc discharges, many researchers have used the exponential growth criterion, often known as the Townsend criterion, where the electron density (n) is assumed to rise by an arbitrary factor of 10^8 from its original value. The output of an optical signal (flashover) is frequently used to determine the breakdown time in previous studies. However, in real situations, a noticeable amount of visual output requires a substantial number density of electrons, suggesting that breakdown occurs earlier.

The distribution of discharge inception and breakdown voltage for various mixing ratios of SF_6/CO_2 with mixing ratios of pure SF_6, $90SF_6/10\%CO_2$, 80% SF_6/20% CO_2, 50% SF_6/50% CO_2, 20% $SF_6/80\%CO_2$, 10% SF_6/90% CO_2, and pure CO_2 at two different pressures (P=1-2 bar) are shown in Fig.2 and 3. It is clear that $90\%SF_6/10\%CO_2$ has the maximum inception and breakdown voltages at P= 1 bar. Moreover, the discharge inception and breakdown voltages decreased with increasing CO_2 content in SF_6.

Additionally, $20\%SF_6/80\%CO_2$ had an inception voltage comparable to that of pure SF_6, but complete breakdown occurred at a significantly lower voltage than pure SF_6. At P= 2 bar, both the initiation and complete breakdown voltages of

The SF_6/CO_2 mixed gas ratio significantly increased. For example, the inception voltage of pure SF_6 increased from 3.7 kV to 6.0 kV and the breakdown voltage increased from 6 kV to 9.9 kV with increasing the pressure from 1 bar to 2 bar. At the higher pressure of 2 bar, the difference between the initiation and breakdown voltages increased for each ratio. At P= 1 bar, the difference between the discharge initiation and breakdown voltages of pure SF_6 is only 2.5 kV which increased to 4 kV with increasing pressure to P= 2 bar. Moreover, with increasing pressure, the difference between the two voltages (initiation and breakdown) for pure SF_6 and $20\%SF_6/80\%CO_2$ increased.

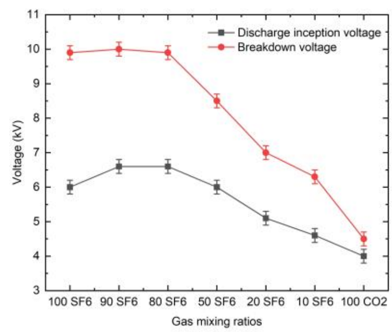

Figure 2 Discharge inception and breakdown voltages of SF_6/CO_2 mixed gas with different mixing ratios at *P*=2bar

A pulse waveform with a mean current of 100µA was recorded for pure SF6 (Fig.4). The development of pulses for the other mixing ratios was like that of pure SF_6. However, a difference was noted in the pulse occurrence time for both pressures. In the initial phase, small pulses with an amplitude of less than 50µA. A large amplitude pulse of greater than 600µA was observed, and then again, the small pulses with lower amplitudes continued to increase until breakdown. The pulse amplitude was low and ranged between 50 and 100 A in the early stages of current pulse production, with a mean discharge capacity of 5 pC. The small-amplitude pulses increase as the mean current increases, and medium-amplitude pulses (with an amplitude of 300–320µA and a mean discharge capacity of 10.5 pC) start to develop. Large-amplitude pulses are produced at a current of 100 µA with

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an amplitude above 650 µA, and the mean discharge capacity is 25 pC). The number of pulses of various amplitudes continues to rise as the mean current rises until gap collapse.

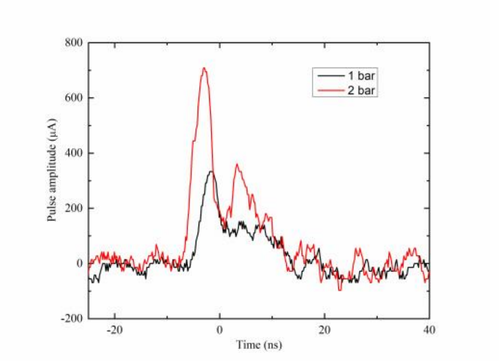


Figure 3 Pulse amplitude of discharge current for SF_6 at 1bar and 2 bars

III. 3D PARTICLE SIMULATION MODEL AND ZENER'S MODEL

In this section, 3D PIC/MCC simulations are performed on the data obtained from the experiments, including the breakdown voltage, computational domain, and electrode tip radius. In the following section, the details of the 3D PIC/MCC simulation model including Zener's model are presented. There are two different kinds of simulation techniques used in the literature for discharge initiation and development in electronegative gases, that is fluid, and kinetic modelling. A particle-in-cell simulation technique was adopted in this study because of its advantage of considering the density fluctuation and stochastic behavior of the streamer discharge. The simulation model *Pamdi3D* [24] used for streamer discharge in air [25] was extended to supercritical fluids to realize field ionization in [26] and was used for streamer discharge initiation in SF_6/CO_2 gas mixtures in the present work. The brief details of the 3D Particle model is given as follows. Electrons are particles, whereas ions are taken as immobile densities in the present simulation model. Because of the low ionization degree in streamer discharges (10^{-4}), only electron-neutral collisions are considered, whereas other collisions such as electron–electron and electron–ion collisions are neglected. The cross-section data for SF_6 and CO_2 were obtained from the SIGLO database on lxcat.net [27]. Collisional probabilities were determined using the null collision method reported in [28]. Furthermore, an adaptive mesh refinement technique [29] was used to refine the layers of the space charge in the streamer head, as shown in Fig. 4. The grid size in each direction is chosen as 101 101 101 and the grid delta is chosen as 10×10^{-6} um comprising the total size of the computational domain 1mm^3. In the following section, the detail of the Zener's model is given. Note that Zener's model is included into the 3D particle model to describe the charge generation mechanism.

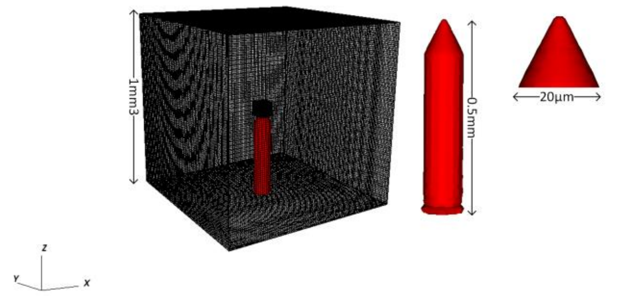


Figure 4 3D Computational domain with needle electrode and tip parameters used in the simulation model.

A. ZENER'S MODEL BASED ON FIELD IONIZATION

Discharge initiation has attracted considerable interest because of its importance in understanding complete breakdown phenomena in dielectric media. It depends on the composition of the insulating media, the distribution of the electric field, and the polarity of the applied voltage. As previously discussed, electron detachment and photoionization are usually adopted for streamer discharge initiation and propagation under pulsed voltages. However, the source of the negative ions for DC voltages is still unknown. Moreover, photoionization does not work efficiently in gases with large quantities of CO_2; therefore, other ionization mechanisms need to be investigated [18]. The field detachment of electrons occurs in the presence of a high applied electric field, which can be attained using a very sharp tip of the needle electrode [14]. In field ionization, electrons and positive ions are produced from a neutral molecule in the presence of a very strong electric field. It works like electron detachment in air; hence, it is adopted for streamer initiation in highly electronegative gases in this work.

The next step is to realize field ionization, which has been performed by including Zener's model into a 3D particle model to investigate positive streamer initiation in an SF_6/CO_2 mixture. Here we want to clarify that Zener's model is only responsible for electron generation depending on the various factors mentioned ahead. It is only one of the sections of the complete 3D PIC/MCC model. Zener's model is only responsible for charge generation whereas the PIC/MCC model contains other sections such as electrode configuration, electric field distribution, meshing information, initial condition etc. mentioned in the start of this section. The Zener model was applied to explore the breakdown initiation in solid insulation materials and was further extended to liquid and supercritical fluids (SCFs) [26, 30, 31]. Zener's model has been used for streamer discharge initiation in SF_6 at different pressures [32]. Zener's field ionization can be described by the following equation:

$$G(\vec{E}) = qn_0|\vec{E}|h^{-1}exp\,(-\frac{\pi^2 m^* a\Delta^2}{qh^2|\vec{E}|})\quad(1)$$

Here, $G(\vec{E})$ represents the electron generation term, q represents the electronic charge, n_0 represent the number of neutral molecules, $\vec{E}$ is the electric field, m is the effective mass of the electron, a is represented by *m*, separation distance between neutral molecules a and Δ is the ionization potential of neutral molecules is Δ. Electron generation from negative ions in gases such as SF_6 and CO_2 is highly field-dependent, and determination of the ignitable density (negative ions in this case) is required. Considering that the number of negative ions increases because of the strong attachment property of SF_6 in the highly stressed area near the needle electrode, we assume n_0 ($1\times10^{20}m^{-3}$) the ignitable density with an ionization potential of Δ = 5 eV, from which electrons and positive ions are generated because of field ionization. Although different values of the ionization potential (Δ) (5 eV-7 eV are considered in the literature, the specific values relevant to field detachment in SF_6 based mixture are challenging. n_o basically represents a small number of neutral molecules (could be considered as impurities present in dielectric media) through which free electrons are generated for positive streamer initiation and propagation. The selection of n_o and a (molecular separation distance) has not yet been quantified for gases, and therefore, assumed values are taken in the present simulation model in the literature. n_o is assumed to be the replica of negative ions present prior to the discharge from which free electrons are generated, such as electron detachment. The velocity of the particles was calculated based on conditions such as CFL. Under conditions such as CFL, particles move less than half the size of a grid cell at time $\Delta t < 1/2\ \Delta x/v_{max}$. V_{max} 9/10th velocity for reduction of fluctuations. The particles were uniformly distributed at the generation position.

IV. RESULTS AND DISCUSSION

A high electric field was generated at the needle tip by applying a positive d.c. voltage to the needle electrode. The electric field at the needle tip was sufficiently high to initiate the ionization process. Electrons propagated towards the needle electrode, leaving heavy immobile positive ions behind them. The electric field due to the space charge resulting from the positive ions combined with the background electric field created another high-field zone in which more ionization occurred at a point away from the needle electrode. Repetition of this physical process results in the formation and propagation of streamer discharge. First, the 3D PIC/MCC-Zener model was used to observe the morphology of streamer discharge in SF_6/CO_2 at two different applied voltages (3.5 kV and 4 kV) as shown in Fig. 6. The regular and obvious structure of the streamer discharge appeared at a higher voltage of 4 kV and below this voltage, the discharge behavior was irregular. Therefore, 4 kV kV was chosen as the optimal value based on the experimental results and was further used in all cases. The results were obtained from the 3D PIC/MCC simulation model in the form *.silo* files and were further processed using volume rendering in *VisIt* software.

The discharge structure at the needle tip was divided into three distinct phases in the simulation results. The first stage is inception cloud formation, the second stage is initiation cloud breaking into the main streamer channels, and the third stage is the subsequent streamer branching from the main streamer channels. Fig. 6 shows the streamer discharge initiation in SF_6/CO_2 mixed gas with mixing ratios of pure SF_6, $90\%SF_6/10\%CO_2$, $80\%SF_6/20\%CO_2$, $50\%SF_6/50\%CO_2$, $20\%SF_6/80\%CO_2$, $10\%SF_6/90\%CO_2$, and pure CO_2 at 3.5 kV. A fine inception cloud appears at the needle tip after 10 ps. There were not enough electrons in the computational domain to trigger the discharge phenomenon until 10 ps. Note that only the tip is shown to save space. The size of the inception cloud increased with increasing CO_2 content in SF_6 however, the shape remained the same, with no distinct variation. After 20 ps, the second phase of streamer discharge appeared, that is, the breaking of the initiation cloud into the main streamer channels. It is clearly shown that the streamer evolved into two stages in the case of pure SF_6 and the third stage was not observed in the given timescale. Only one main streamer channel appeared in the second stage for pure SF_6. The number of main streamer channels increased with increasing CO_2 in SF_6 and was higher for pure CO_2. With a higher content of CO_2, the third stage of streamer, that is, subsequent streamer branching from primary streamer channels, started to appear at 30 ps and later times. The structure of the streamer discharge with obvious branching is clearly shown in the top view of Fig. 5.

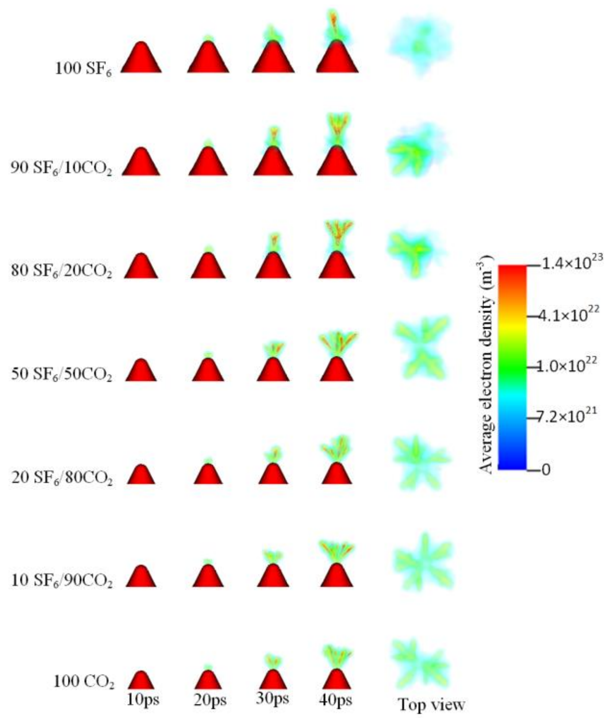


Figure 5. The structure of positive streamers in SF_6/CO_2 at 3.5kV and P=1bar

Side and top views of the streamers at the tip in SF_6/CO_2 at 4 kV and 1 bar are shown in Fig. 6. A streamer discharge in the shape of a tree and sharp filaments appeared at the needle tip. The streamer discharge stages were similar, with no distinct changes. However, the size of the avalanche, number of primary streamers, and subsequent streamer branching increased with the applied voltage. Like 3 kV, the size of the inception cloud, streamer channels (number and length), and subsequent branching decreased with decreasing SF_6 content in CO_2. Moreover, streamers propagate axially in the direction of the electric field at lower voltages, and with increasing voltage, streamers tend to propagate in both the axial and radial directions. In addition, at 3.5 kV, streamer branches are more compact, and the distance between them increases with increasing applied voltage. The streamer structure appearing at the needle tip in this work is quite similar to the structure of the streamer discharge obtained through experiments in gases [33].

The average electron density profile in the positive streamer discharge in the SF_6/CO_2 mixed gas at separate times is plotted at 3.5 kV and 4 kV in Fig. 7. Positive streamer initiation and propagation are dictated by the source of the free electrons and their rate of generation. For the calculation of free electrons, Zener's model was used, which mainly depends on the electric-field intensity. Other parameters for electron generation mainly depend on the ignitable density of molecules, which are assumed to behave like negative ions in air, and their ionization potential. In the present simulations, at 3.5 kV, the average electron density was the minimum for pure SF_6 and then increased with decreasing SF_6 content and increasing CO_2 ratio. This is justified by the strong electron attachment property of SF_6 as it absorbs electrons quickly as soon as they are generated. At 4 kV the overall electron density increased with the applied voltage. A high applied voltage results in a high electric field near the electrode tip. A high electric field results in more free electrons. Similarly, at 4 kV, the number of electrons increases with decreasing SF_6 and increasing CO_2 content in the mixture.

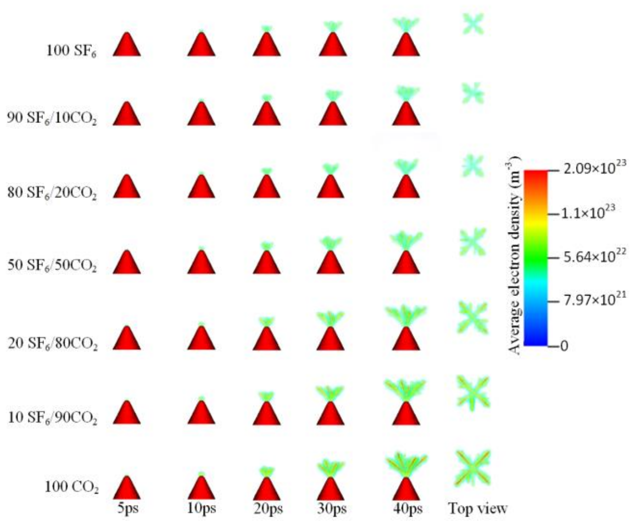
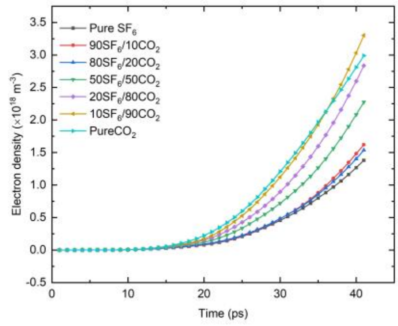
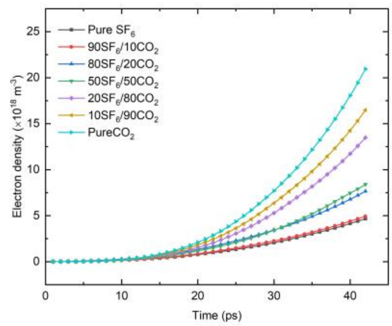


Figure 6 **The structure of positive streamer in SF_6/CO_2 at 4kV and P=1bar**



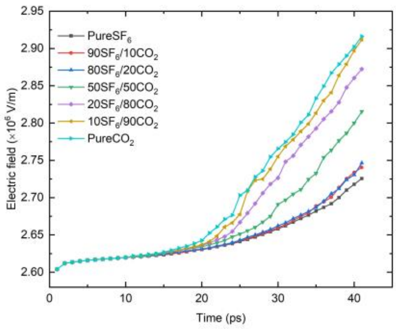
(a)



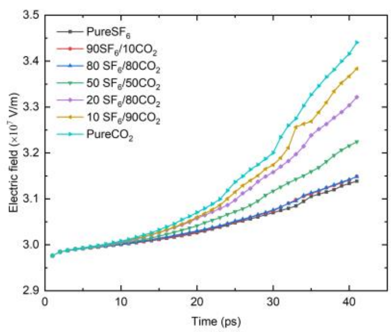
(b)

The Figure 7 **Average electron density in streamer discharge in SF_6/CO_2 at (a) 3.5kV and (b) 4kV**

Electric field plays a critical role in the generation of free electrons and was calculated using Poisson's equation in the present 3D simulation model. Fig. 8 shows the average electric field distribution for the positive streamer in SF_6/CO_2 at two different applied voltages (3.5 kV and 4 kV). The initial electric field was higher at 4 kV causing fast generation of free electrons because of field ionization, resulting in quicker formation of streamer discharge and its subsequent splitting into branching. The average electric field was minimal for pure SF_6 at both applied voltages and increased with decreasing SF_6 in CO_2. The generation of free electrons is highly dependent on the electric field intensity in Zener's model; therefore, it works properly under a highly non-uniform electric field. The overall trend of the electron density and electric field distribution in the SF_6/CO_2 gas mixture obtained from the 3D PIC/MCC simulation model is consistent with the results in the literature, that is, the electric field and electron density increased with increasing CO_2 concentration in SF_6.



(a)



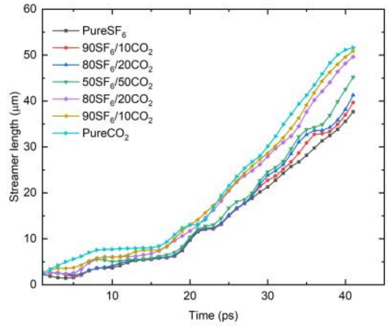
(b)

The Figure 8 Average electric field of streamer discharge in SF_6/CO_2 with different mixing ratios at (a) 3.5kV and (b) 4kV

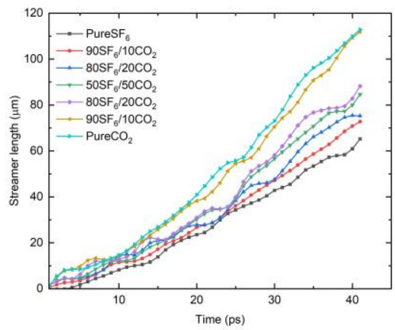
Length is a streamer characteristic used to assess the formation and propagation of streamer discharge under different applied conditions. In this study, the streamer length with the maximum electric field is calculated as follows:

$$L(t) = \sqrt{\left(x_{max}(0) - x_{max}(t)\right)^2 + \left(y_{max}(0) - y_{max}(t)\right)^2 + \left(z_{max}(0) - z_{max}(t)\right)^2} \quad (2)$$

Here, *L(t)* represents the total streamer length, $x_{\max}$, $y_{\max}$, and z_{max} are the components of the streamer length at the maximum electric field. *VisIt* software was used to locate the coordinates with the maximum electric field first, and then the streamer length was calculated using Equation 2. Fig. 10 shows the streamer length with maximum electric field for the SF_6/CO_2 mixed gas with different mixing ratios at atmospheric pressure for two different applied voltages of 3.5 kV and 4 kV. For both applied voltages, the maximum streamer length was calculated for pure CO_2 which decreased with increasing SF_6 content in CO_2. At higher voltages, a higher generation of electrons occurs, resulting in quicker formation and propagation of streamer discharge, as depicted in Fig. 9. The different stages of streamer discharge may correlate with the streamer length. Until 20 *ps*, the first phase of the streamer avalanche formation occurred at 3.5 kV and the remaining stages occurred after 20 ps. For 4 kV, the time was reduced to 10 ps, which means that the streamer formed quickly with increasing applied voltage.



(a)



(b)

Figure 9 Streamer length on coordinates with maximum electric

A. EFFECT OF PRESSURE

In this section, the effects of pressure on the streamer morphology, electron density, and electric field at 4 kV. Fig. 10 shows the structure of the streamer discharge in SF_6/CO_2 with varying mixing ratios for 4 kV at *P*= 2 bar. The structural morphology remains unchanged at higher pressures. As in the previous case, that is, at P= 1 bar, three distinct stages of streamer discharge appeared at the tip of need electrode. However, with increasing pressure, the subsequent branching decreased compared to that at lower pressure. With increasing pressure, the inception and breakdown voltages increase, as shown in Fig. 3. Moreover, the average electron density and electric field decrease at *P*= 2 bar, as shown in Fig. 11. It

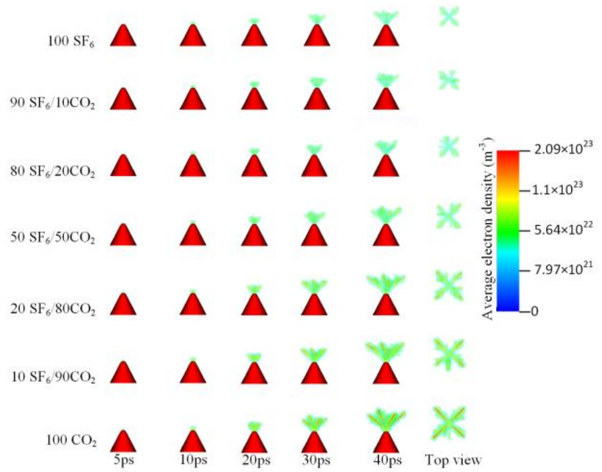
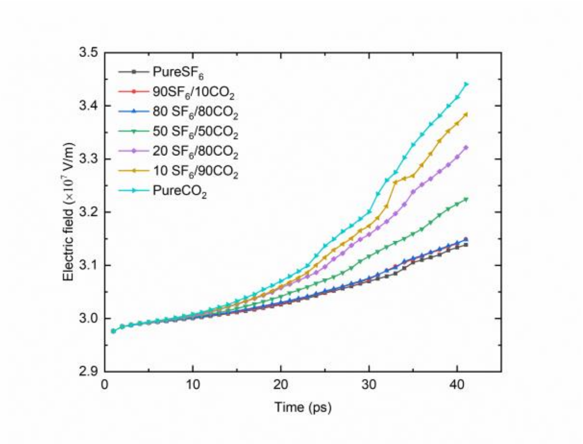
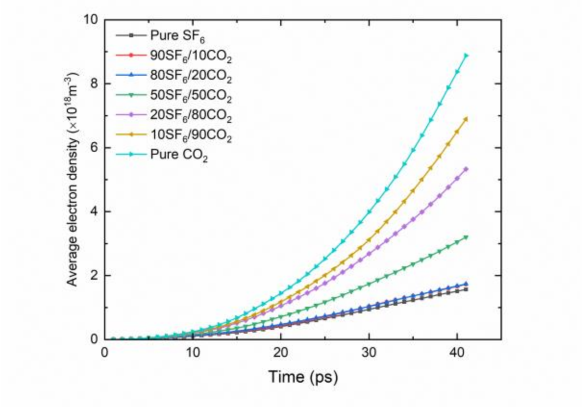


Figure 10 **Structure and electron density of positive streamer in SF_6/CO_2 (4kV and P=2bar)**



(a)



(b)

Figure 11 **(a) Average electron density and (b) average electric field for positive streamer discharge in SF_6/CO_2 with different mixing ratios for 4kV at 2 bar.**

V. CONCLUSION

This work includes an experiment to measure the discharge initiation and breakdown voltages in SF_6/CO_2 mixed gas with different mixing ratios at two different pressures (1 bar and 2 bar). The purpose of the experiments was to obtain the preliminary breakdown voltage data for the simulation model. Second, the positive streamer initiation in the SF_6/CO_2 gas mixture was investigated by considering Zener's model in the 3D PIC/MCC model. It was assumed that Zener's model worked similarly to field detachment of electrons in air. The main findings of this study are as follows.

- The experimental results revealed that the discharge initiation and breakdown voltages increased with an increase of 10% and 20% CO_2 in SF_6 and decreased significantly with increasing CO_2 concentrations higher than 50% at both pressures. However, the discharge initiation voltage of 20%SF_6/80%CO_2 is comparable to that of pure SF_6 at P= 1 bar. Moreover, the difference between the discharge initiation and breakdown voltages for all the mixing ratios increased with increasing pressure.
- The 3D simulation results indicate that tree-like streamer discharges with subsequent branching appeared for all mixing ratios at both applied voltages (3.5 kV and 4 kV) expect for pure SF_6 at 3.5 kV.
- Electron density, streamer length and electric field increased with increasing CO_2 in SF_6.
- At P= 2 bar, the structure of the streamer remains unchanged; however, the other parameters decrease significantly.

In conclusion, Zener's model based on field ionization, such as field detachment of electrons in air, worked well for SF_6/CO_2 mixed gas when the electric fields were highly non uniform. However, this method has some limitations and requires further investigation in the presence of uniform fields. Experimental validation of Zener's parameter for electronegative gases such as SF_6 and CO_2 is an open research question. This research would be helpful in exploring the source of free electron generation in gases with higher CO_2 content than photoionization.

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