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Schlieren Images of Negative Streamer and Leader Formations in CO_2 and a CF_3I-CO_2 Electronegative Gas Mixture

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Featured Application: Negative streamer and leader formations in electronegative gas mixtures.

Abstract: In electrical networks, SF_6 gas is currently used to insulate high-voltage equipment, however, due to its high environmental impact, new alternatives such as CO_2 and electronegative gas mixtures such as CF_3I-CO_2 are being trialled to replace SF_6 and create a sustainable energy system. A high-voltage lightning impulse (1.2 µs/50 µs) was used to approximate the disturbance in a high-voltage electrical network caused by a lightning strike and helped to identify the likely streamer and leader formations in different gases insulating a piece of gas insulated switchgear. In this paper, the theoretical and practical aspects of electrical streamer and leader formations in pure CO_2 and an electronegative gas mixture of CF_3I-CO_2 are examined using schlieren videography in small length rod-plane gas gaps between 20 and 50 mm in length. Schlieren allows the examination of gas density in streamer formations and for the differences in weakly attaching gases, such as CO_2, and electronegative gas mixtures, such as CF_3I-CO_2, to be studied. The gas pressure is varied in order to examine the differences in streamer and leader formation as the gas density is varied and hence the probability of electron collision is varied.

Keywords: schlieren; streamer and leader formation; dielectric insulation gases; gas insulated switchgear (GIS)

1. Introduction

In the electrical power industry, sulphur hexafluoride (SF_6) is being used to insulate high-voltage power apparatus and equipment in increasing amounts [1], however, it is facing growing scrutiny considering its negative environmental attributes. It has been approximated that SF_6 has a global warming potential 23,500 times that of carbon dioxide (CO_2) [2] and an atmospheric lifetime of 3200 years [3], making it one of the most potent greenhouse gases known to humankind. In recent years, research institutions and the power industry have been investigating gas mixtures of electronegative alternatives [4–9] in order to find a suitable replacement insulation gas which is environmentally friendly and has a similar insulation strength and electrical characteristics to that of SF_6. One such gas is trifluoroiodomethane (CF_3I) which has a global warming potential of <5 [10] and an atmospheric lifetime of <2 days [10] making it considerably more environmentally friendly than SF_6, however, much more knowledge of its electrical attributes is needed. In order to understand its electrical characteristics, it is important to further our knowledge of practical formation of leaders and streamers in gas mixtures of CF_3I-CO_2 being trialled as an insulation alternative to SF_6. It is also crucial to understand how pure CO_2 performs separately compared to CF_3I-CO_2 and how these compare to streamer and leader theories for SF_6. For comparison, the mechanisms and different theories of streamer and leader initiation and development in both positive and negative scenarios in air or SF_6 are given in [11,12]. A gas mixture of CF_3I with a buffer gas such as CO_2 is required to decrease the liquefaction temperature of the gas mixture which otherwise would be too high for use in practical high-voltage equipment.

In [7,12–14], the effective ionization coefficients of CO_2, Air, 30:70 CF_3I-CO_2, pure SF_6 and CF_3I have been summarised for known gases and calculated using BOLSIG for CF_3I gas mixtures. It is shown in Figure 1 that the lowest critical reduced field strength, at which the net ionisation is greater than the attachment, is lowest for CO_2 and then air, with the highest being for 30:70 CF_3I-CO_2 of all gases/gas mixtures used for practical testing in this paper. Pure SF_6 has a theoretical critical reduced field strength of approximately 89 kV/cm bar [12] compared to air which is about 27 kV/cm bar or 23/32 kV/cm bar (rms/max) [12], hence its dielectric strength is approximately 3 times that of air because no net ionisation can occur unless the electric field strength exceeds this value. For pure CF_3I, the critical reduced electric field strength is approximately 108 kV/cm bar [7,14], hence its dielectric strength is around 1.2 times that of SF_6, however, this critical reduced electric field strength reduces when CF_3I is mixed with CO_2 for a gas mixture ratio of 30:70, as shown in Figure 1, which gives an idea of its practically demonstratable breakdown strength, as shown in [8,9]. It is shown in Figure 1 that pure SF_6 and CF_3I are insulation mediums where ionisation builds very rapidly if the critical electric field strength is exceeded, whereas CO_2 and Air have a much slower building rate of ionisation. A gas mixture of CF_3I-CO_2 has a very sharp rise of effective ionisation coefficient when compared to pure CO_2.

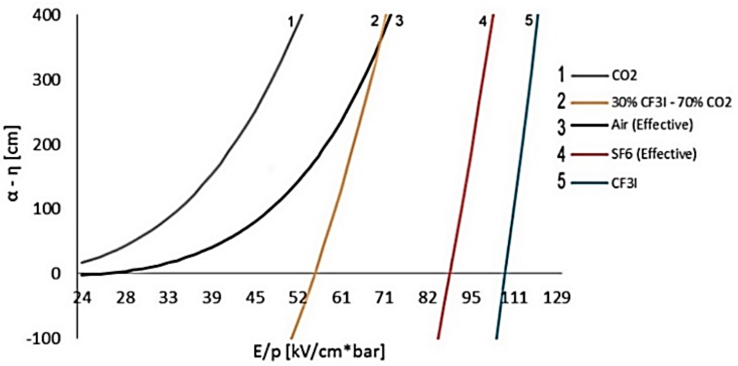


Figure 1. Effective ionisation coefficients of CO_2 [12], Air [12], 30:70 CF_3I-CO_2 [7,13], SF_6 [12] and CF_3I [7,13,14].

2. Practical Test Arrangement

In the following results, the electrical performance of an insulation gas was tested using an applied standard lightning impulse voltage (1.2 µs rise time to peak and 50 µs time to half voltage) with the conditions as described in the electrical standard IEC 60060-1 [15]. A measurement of the applied negative impulse voltage was recoded using an oscilloscope connected to a high-voltage capacitive divider, as shown in Figure 2. A current transformer (CT) was also used to take a reading of the current which was induced on the earth strap connected to the grounding plane and confirm a CO_2 no-breakdown scenario as streamer formation occurs across the rod-plane electrodes (partial discharge), as shown in Figure 2. For a CF_3I-CO_2 gas filling with the same electrode configuration, no separate current event could be recorded and, therefore, no comparison can be made, this could indicate the streamer formation occurs very rapidly in this gas mixture, however, it is not possible to conclude this without higher resolution time measurements.

The rod-plane electrode gap consisted of a 10 mm diameter rod with a 5 mm tip radius and a 135 mm diameter circular plane electrode with a 10 mm radius edge. A stainless-steel pressure vessel with a high-voltage bushing allowed the connection of the impulse generator to the rod electrode inside the vessel whilst on the opposing plane a dedicated grounding connection, isolated from the pressure vessel wall, was used to ground the electrode to the impulse generator, as shown in Figure 3. The pressure vessel was evacuated before each test to a pressure of <1 mbar and the vessel filled directly from evacuated hose connections and dedicated gas cylinders depending on the gas-gas mixture ratio which was achieved using an indicated pressure reading correct to 2 decimal places. The gas mixture was achieved using a 30% pressure − 70% pressure mixture as opposed to using a weight-weight measurement. The pressure vessel had two opposing windows which block UV light, as CF_3I degrades under UV light, which allows for the schlieren test setup to be placed across these windows. The schlieren test arrangement consists of a point LED light source, two biconvex lenses, a knife edge and a high-speed camera [16] placed around the pressure vessel, as shown in Figure 3. Similar schlieren experiments are shown in [17–19], however, few experiments have been conducted using this technique to study electronegative gas mixtures.

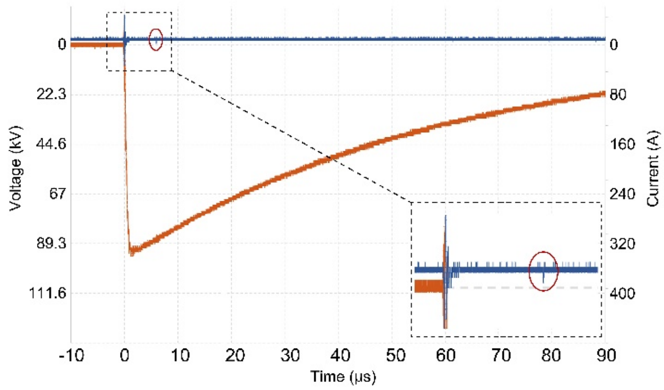


Figure 2. Voltage and current measurements for a 93 kV negatively applied lightning impulse across a 40 mm gas gap filled with 0.15 MPa CO_2.

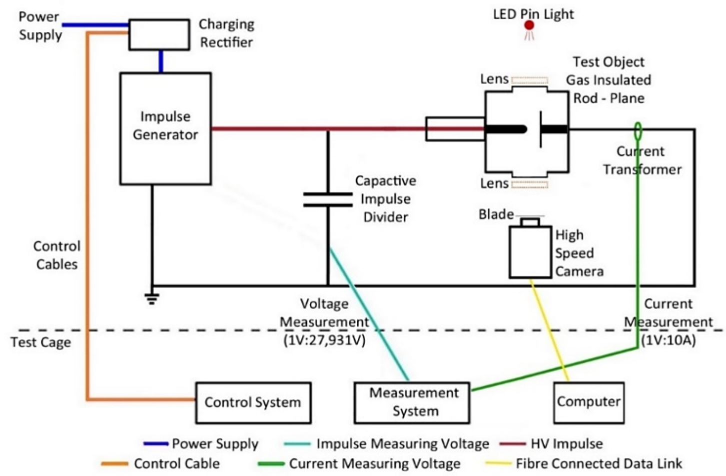


Figure 3. Test arrangement including high-voltage impulse generator, schlieren setup and pressure vessel.

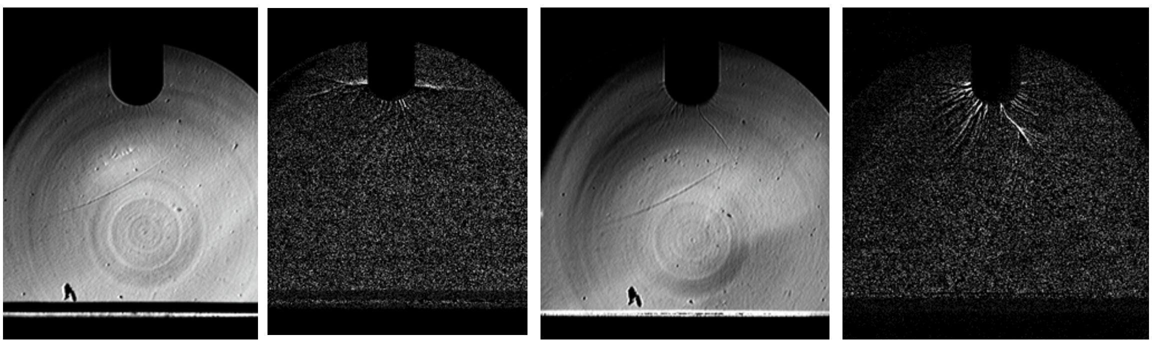
The high-speed camera records monochrome images at a resolution of 512 × 512 pixels with a frame rate of 20,000 fps or 1 frame every 50 μs. This arrangement of schlieren video capture is a method of observing the gas as it moves around streamer or leader channels. The gas in the schlieren images recorded moves at a much slower rate than the light output of such streamer/leader events, which only last for one frame at this exposure time. It is, therefore, possible to discuss streamer/leader development using a much slower camera exposure time for schlieren images than is typical for light observation of partial arcing events.

The schlieren images recorded are shown as both unedited versions with high contrast and as subtracted images where the frame shown was subtracted from the first blank frame of the video therefore highlighting pixels that were different i.e., areas where streamers were formed. (Supplementary Materials Figures S1–S6 are Data—Schlieren Images of Negative Streamer and Leader Formations in CO_2 and a CF_3I-CO_2 Electronegative Gas Mixture). The image subtraction technique also helped to remove artefacts present in both images, such as concentric rings resulting from the LED point source, to produce a cleaner dataset. The technical method used in this paper is further described in [20].

In the first instance streamer and leader formation was examined using pure CO_2 taken from a cylinder of 99.8% purity [21]. Following this, experimentation using gas mixtures of 30% partial pressure CF_3I at 99.9% purity [22] and 70% partial pressure CO_2 were undertaken.

3. Negative Streamer and Leader Formation in CO_2 and CF_3I-CO_2

Following experimentation, a comparison between an applied negative lightning impulse in CO_2 (Figures 4a,b and 5a,b) and a 30:70% CF_3I-CO_2 gas mixture (Figures 4c,d and 5c,d) was examined for a 40 mm rod–plane gas gap. It was found that at these short gap lengths it was very difficult to obtain schlieren videography without a breakdown event occurring when a positive lightning impulse was applied to the rod-electrode and that videography could only be obtained under negative voltage conditions. It is likely that, because the initiatory electron in a positive streamer formation is progressing as part of an avalanche towards the rod electrode and towards a high field region, streamers and eventual breakdown is rapid and far reaching once the critical reduced field strength has been exceeded. However, in negative polarity, the initiatory electrons are moving outwards from the rod electrode towards an electric field region of decreasing intensity, so progression is more difficult. Under lightning impulse conditions, where the applied voltage is often much higher than under AC or DC stress, the field intensity around the electrode is higher and occurs very rapidly for the test conditions used in the events shown. For a positive streamer, the initiatory electron must exist in the gas between the electrodes to commence streamer formation but in electronegative gases electrons are strongly attached as negative ions and so it is harder to form free electrons without the chance of cosmic rays, background radiation or one of many theorised mechanisms. In gases such as air and SF_6 it has been shown that the positive impulse conditions are a valuable reference for high-voltage testing because it has a lower breakdown voltage than with negative polarity which increases linearly with gap length, however, in CF_3I gas mixtures it has been shown that under some electrode conditions the breakdown voltage can be lower in negative polarity rather than positive [23].



(a) (b) (c) (d)

Figure 4. 0.1 MPa. Schlieren images taken of no-breakdown events in a rod-plane electrode configuration with a 40 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**a**) and (**c**) Unedited image with contrast. (**b**) and (**d**) Subtracted image highlighting areas of difference. (**a**) and (**b**) CO_2 negative 70 kV −0.1 MPa. (**c**) and (**d**) 30:70% CF_3I-CO_2 negative 110 kV.

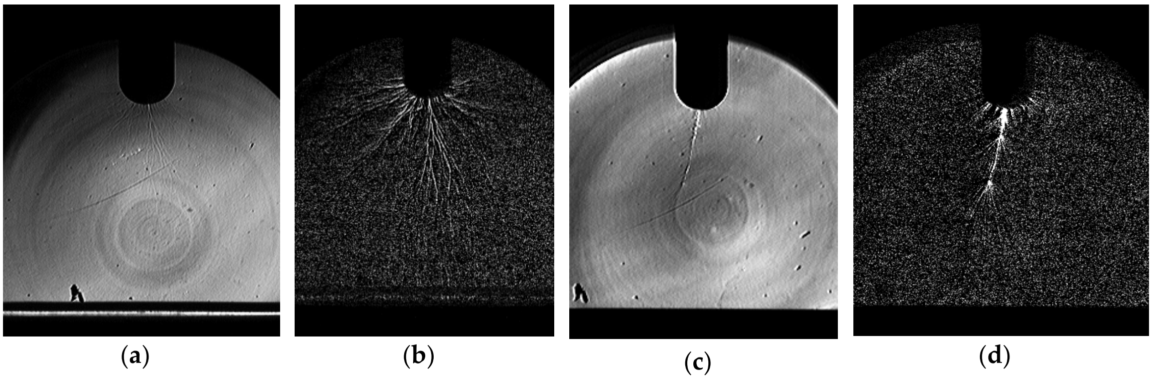
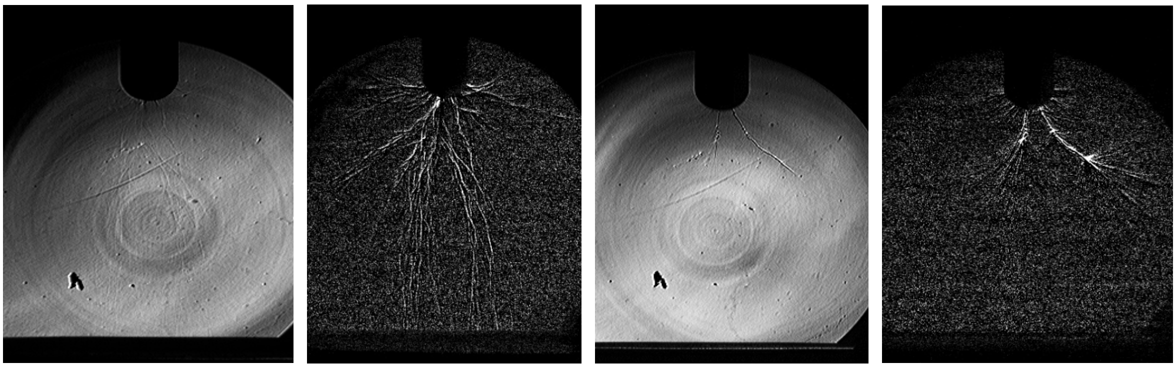


Figure 5. 0.15 MPa. Schlieren images taken of no-breakdown events in a rod-plane electrode configuration with a 40 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**a**) and (**c**) Unedited image with contrast. (**b**) and (**d**) Subtracted image highlighting areas of difference. (**a**) and (**b**) CO_2 negative 93 kV −0.15 MPa. (**c**) and (**d**) 30:70% CF_3I-CO_2 negative 119 kV.

In CO_2 (Figure 4a,b and Figure 5a,b), streamers form distinct multi-channels for negative streamer progression away from the rod caused by electrons moving outwards into the electric field of decreasing intensity. These negative streamer formation filaments in pure CO_2 are not the same as in CF_3I-CO_2 gas mixtures (Figure 4c,d and Figure 5c,d) where there appears to be fewer streamers. This gives the impression that the first stage streamer length can spread further into the CO_2 gas gap as part of the avalanche along the field gradient. This is likely caused by the critical reduced electric field strength being lower in CO_2 than in CF_3I-CO_2, allowing for net ionisation and streamer development to occur at a lower applied voltage. It is also important to note that the molecular size and mass of a CO_2 molecule is less than CF_3I, this means that a CO_2 molecule has a higher molecular diffusion rate than CF_3I but has less mass, therefore exerting the same pressure as a heavier, slow moving but larger sized CF_3I molecule. This means that a CO_2 and CF_3I-CO_2 mixture have the same number of molecules in the same volume when filled at exactly the same pressure and temperature. The frequency of an electron collision with a neutral molecule during streamer formation is dependent on the temperature, pressure, mass, size of the molecule and its molecular diffusion rate.

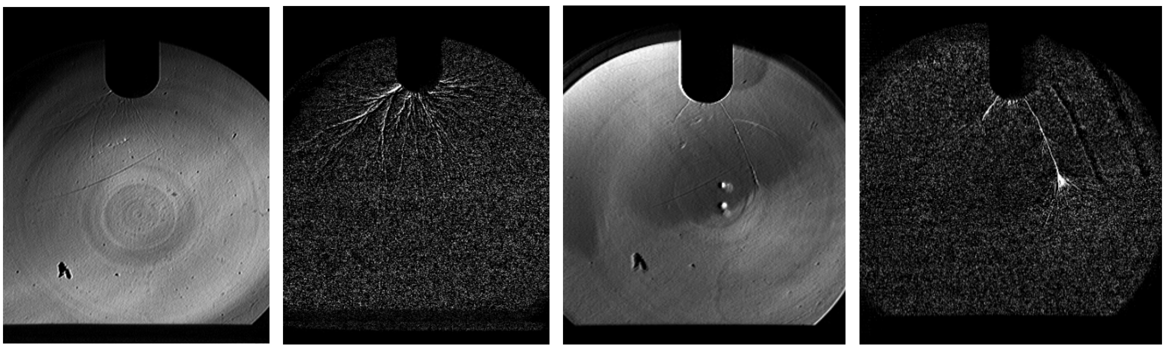
In 30:70% gas mixtures of CF_3I-CO_2, as shown in Figure 4c,d and Figure 5c,d, the addition of CF_3I to CO_2 as a mixture causes streamer growth around the electrode to be considerable stunted compared to pure CO_2. It also appears that in CF_3I-CO_2 gas mixtures the formation of stepped leaders from the streamers are present whereas this is not the case for CO_2 where only streamers are present. In other electronegative gases, such as pure SF_6, a similar stepped leader process can be observed in short point-plane 20–50 mm gaps [12] and at pressures of 0.15 MPa typical of gas insulated switchgear (GIS). In GIS it has been found that the breakdown voltage under fast-fronted surges in non-uniform gaps was determined by direct leader inception and propagation in the absence of pre-existing corona space charge [12]. In fast-fronted impulse conditions, the voltage passes very quickly through the theoretical streamer onset level and the initial intense streamers can lead to the formation of a highly ionised leader channel before there is time for space charge stabilisation of the field at the tip of the electrode [12]. As shown in Figure 4c,d and Figure 5c,d, the first stage streamer progression was further from the electrode when the gas density was lower i.e., the pressure was 0.1 MPa rather than when the pressure was raised to 0.15 MPa. It can also be shown that when the applied negative impulse voltage was increased from Figure 4c,d to Figure 5c,d that the leader formation in CF_3I-CO_2 progressed further across the gas gap due to an increase in the electric field intensity at the electrode tip and the energy imparted on the initiatory electron avalanche.

In Figures 6 and 7, the gas gap distance was increased to 50 mm. As with the 40 mm gap, it can be shown that, at 50 mm, a 30:70% CF_3I-CO_2 gas mixture forms stepped leader channels across the electrodes and during no-breakdown events forms first stage and subsequent stages of streamer propagation, in particular this is shown in Figure 6c,d. In SF_6, the length of the initiatory and subsequent stages of streamers determines the length of that step of the leader channel which propagates into the gap in typical steps of a few millimetres until streamer activity is too weak to form a further channel step [24]. In CF_3I-CO_2 it seems from Figure 6c,d and Figure 7c,d that stepped leaders at voltages between 125–132 kV can form a total leader channel approx. 30 mm long across the 50 mm gap and that the probability of bifurcation (two leader channels) seems to increase with the applied voltage level/electric field intensity.



(**a**) (**b**) (**c**) (**d**)

Figure 6. 0.1 MPa. Schlieren images taken of no-breakdown events in a rod-plane electrode configuration with a 50 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**a**) and (**c**) Unedited image with contrast. (**b**) and (**d**) Subtracted image highlighting areas of difference. (**a**) and (**b**) CO_2 negative 90 kV. (**c**) and (**d**) 30:70% CF_3I-CO_2 negative 125 kV.



(**a**) (**b**) (**c**) (d)

Figure 7. 0.15 MPa. Schlieren images taken of no-breakdown events in a rod-plane electrode configuration with a 50 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**a**) and (**c**) Unedited image with contrast. (**b**) and (**d**) Subtracted image highlighting areas of difference. (**a**) and (**b**) CO_2 negative 98 kV. (**c**) and (**d**) CF_3I-CO_2 negative 132 kV.

For CO_2 in Figure 6a,b and Figure 7a,b, the pressure was increased from 0.1 to 0.15 MPa, in order to achieve the impulse voltage required to cause an ionisation streamer event the applied voltage was increased from 90 to 98 kV. It also appears that, as the pressure was increased, the length of the first stage streamers was decreased. This confirms the impression that the probability of ionisation from a single collision will depend on the given energy of the electron (i.e., applied impulse voltage) and the number density of the gas (i.e., pressure) [12]. In Figure 4a,b for CO_2, it can be shown that although the pressure is low there was a short streamer length which was due to the applied impulse voltage level being relatively low at 70 kV compared to all other cases presented in this paper. However, when the CO_2 pressure was increased to 0.15 MPa, as shown in Figure 5a,b, the streamer length appears to increase but this was actually due to the much larger applied impulse voltage of 93 kV which seems to have a significant impact on the gases ability to form longer streamer channels than in Figure 4a,b.

4. Discussion of Negative Streamer and Leader Formation in CF_3I-CO_2

Following the experimentation discussed in the previous section, it is important to note that the first frame captured in the video recorded for most lightning impulse events contains not only the schlieren image but the emitted corona visible light, so is often much brighter along the leader channel and appears to have a wider leader channel than all subsequent frames for all gases used. Further analysis of corona light emission time is given in reference [20] where a dual camera system was used to record schlieren and light emissions simultaneously. In Figure 8, the first image captured of the leader was wider and brighter than the subsequent frames because of visible corona light emission. This light is normally seen and captured by high speed cameras set up for visible/UV range capture only, whereas the schlieren effect is invisible to the naked eye. All other figures shown in Section 3 of this paper depict the first frame of schlieren only (i.e., frame 2 of the complete video recording) as it is much easier to show the shape and formation of the streamers and leaders without corona light emission.

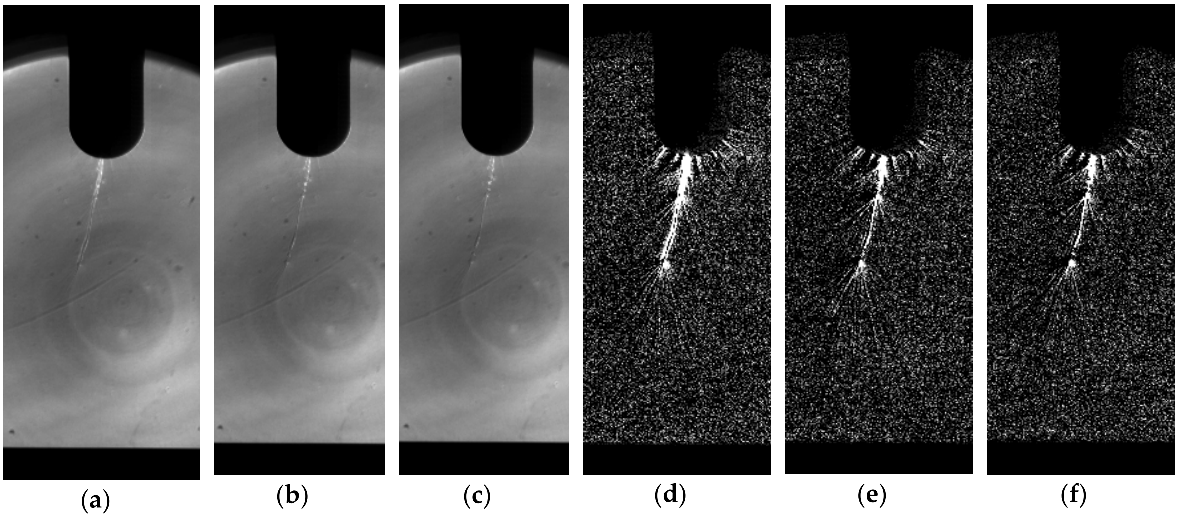
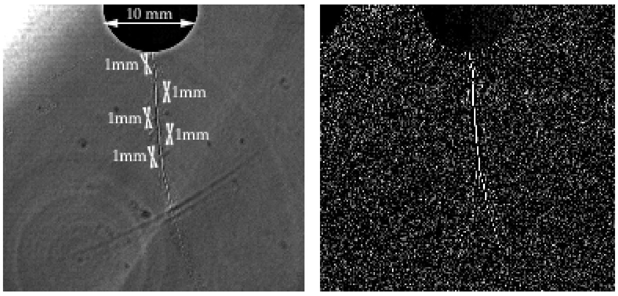


Figure 8. 30:70% CF_3I-CO_2 negative 119 kV −0.15 MPa. (**a**) and (**d**) Schlieren images taken of no-breakdown event highlighting visible corona. (**b**–**d**) and (**f**) Schlieren only in the rest of the subsequent images. Rod-plane electrode configuration with a 40 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**a**–**c**) Image with contrast. (**d**–**f**) Subtracted image highlighting areas of difference.

For SF_6 it has been shown that short leaders progress across the gas gap in typical steps of millimetres [24]. In Figure 9a, schlieren video was obtained by using the high-speed cameras manual zoom to focus on just the tip of the rod in the same test arrangement. In Figure 9, it is shown how large 1 mm steps would be if this was the case for an electronegative gas mixture of 30:70% CF_3I-CO_2. The CF_3I-CO_2 gas mixture appears to fit this theory, however, it is difficult to conclusively show that this holds in all cases without higher resolution and more examples. It is also difficult to state this for certain because the leader could be progressing in three dimensions forwards and backwards as well as downwards in the image, so it is hard to ascertain exact leader step lengths.

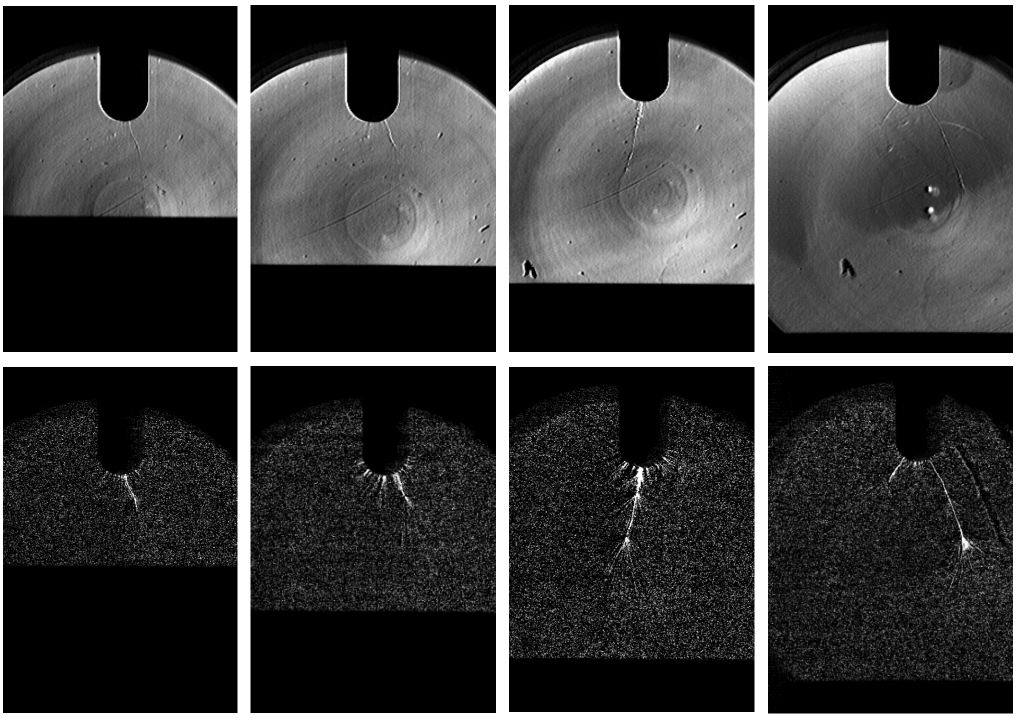


(a) (b)

Figure 9. (**a**) Schlieren image in CF3I-CO_2 125 kV 0.1 MPa taken of no-breakdown event in a rod-plane electrode configuration with a 50 mm gas gap subjected to a negative standard lightning impulse voltage waveform. (**b**) Subtracted image highlighting areas of difference.

5. Negative Streamer and Leader Formation in Varying Gas Gap Lengths of CF_3I-CO_2

For a 30:70% CF_3I-CO_2 gas mixture it was possible to record a variety of gas gap lengths between the rod-plane electrodes between 20–50 mm in 10 mm increments. This was not possible for CO_2 in the 20 and 30 mm gas gap, likely because the first stage streamer formation is too long and bridges the whole gas gap between electrodes. In a CF_3I-CO_2 gas mixture, the first stage streamer length is much shorter than in CO_2, with a higher critical reduced field strength, meaning that more energy is required for streamers to form. In Figure 10a–d, it can be shown that, under an applied negative lightning impulse voltage, a rod-plane gap insulated with CF_3I-CO_2 exhibits streamer and stepped leader formation across all 20–50 mm gas gaps at a pressure of 0.15 MPa.



(a) (b) (c) (d)

Figure 10. (**a**) CF_3I-CO_2 20 mm 80 kV −0.15 MPa, (**b**) CF_3I-CO_2 30 mm 110 kV −0.15 MPa, (**c**) CF_3I-CO_2 40 mm 119 kV −0.15 MPa, (**d**) CF_3I-CO_2 50 mm 132 kV −0.15 MPa. Schlieren images taken of no-breakdown events in a rod-plane electrode configuration in a 30:70% CF_3I-CO_2 gas mixture with a varying gas gap subjected to a negative standard lightning impulse voltage waveform. Top row—unedited image with contrast. Bottom row—subtracted image highlighting areas of difference.

In Figure 10a–d, it can be shown that for streamer formation to occur as the gas gap was increased so too does the applied voltage need to increase from 80 kV for 20 mm to 132 kV for a 50 mm gap. With a constant pressure of 0.15 MPa, it can be shown that as the applied voltage is increased with gap length this leads to an increased length of stepped leader channel which progresses further across the insulation gas. This indicates the distance that an electron avalanche, streamer filament and stepped leader can progress into an electronegative gas mixture is highly dependent on the applied impulse voltage in negative polarity and therefore the electric field strength. In electronegative gases such as CF_3I and SF_6, it is also true that the steep slope of their effective ionisation coefficients means that once the reduced field exceeds a critical reduced field strength the growth of ionisation in the leader channels is very strong which, in practical terms, means that non-uniform fields or very sharp protrusions may initiate complete breakdown of a gas insulated system.

6. Conclusions

In this paper, it has been shown that CO_2 negative streamers form more multi-path streamer filaments than in CF_3I-CO_2, giving the impression that the initial first stage electron can progress further into the gas gap as part of the avalanche along the field gradient. It also appears that as the pressure is increased the length of the initiatory streamers is decreased. This confirms the impression that the probability of ionisation from a single collision will depend on the given energy of the electron (i.e., applied impulse voltage) and the number density of the gas (i.e., pressure). In all gases and gas mixtures used, the applied voltage was increased as the pressure was increased in order to increase the electric field strength and excite streamer formation.

In 30:70% gas mixtures of CF_3I-CO_2, the addition of CF_3I to CO_2 to form a mixture causes streamer growth around the electrode to be considerably stunted compared to pure CO_2 and there is formation of stepped leaders. In CF_3I-CO_2, the first stage negative streamer progression reaches further into the gas gap between the electrodes when the gas density is lower i.e., the pressure is 0.1 MPa than when the pressure is raised to 0.15 MPa. In CF_3I-CO_2, when the applied negative impulse voltage is increased the leader formation progresses further across the gas gap due to the increase in electric field at the electrode tip and the energy imparted on the first stage electron avalanche. Under an applied negative lightning impulse voltage CF_3I-CO_2 exhibits streamer and stepped leader formation across all 20-50 mm gas gaps at a pressure of 0.15 MPa, which is not the case in CO_2 where first stage streamers are likely too long to record. In the first frame of the recorded images, the streamers depicted show the schlieren effect but also show the emitted visible light radiation from electron attachment so in most examples the second frame of just the schlieren effect is used.

This work has provided valuable insight into the use of pure CO_2 and the use of electronegative gas mixtures, such as CF_3I-CO_2, as a potential replacement for SF_6. This work demonstrates that under lightning conditions on the electrical network electronegative gas mixtures of CF_3I-CO_2 when used in gas insulated switchgear would behave similarly to SF_6 by producing stepped leader channels. Future designs of switchgear insulated with electronegative gas mixtures, such as CF_3I-CO_2, can be adapted by following similar electric field and electrode geometry design principles as those currently undertaken with SF_6.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/22/8006/s1, Figure S1: CO_2 0.1 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform; Figure S2: CO_2 0.15 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform; Figure S3: 30–70% CF3I-CO_2 0.1 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform; Figure S4: 30-70% CF3I-CO_2 0.15 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform; Figure S5: Technical Air 0.1 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform; Figure S6: Technical Air 0.15 MPa Schlieren images taken of no-breakdown events in a rod-plane electrode configuration subjected to a standard lightning impulse voltage waveform.

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