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Breakdown Characteristics of C₃F₇CN/CO₂ Gas Mixtures in Rod-Plane Gaps

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Abstract-Sulphur hexafluoride (SF₆) is an excellent dielectric medium that has been extensively used in gas insulated high voltage equipment. However, due to its high environmental impact, it is increasingly important to find an environmentally friendly alternative to SF₆ in the electrical industry. C₃F₇CN, which shares similar physical and chemical properties as SF₆, is considered to be a viable candidate for applications in gas insulated equipment. The high boiling point of C₃F₇CN indicates that it has to be used as part of a mixture with a buffer gas such as CO₂. This paper provides an overview on the breakdown performance of C₃F₇CN/CO₂ mixtures in non-uniform field. Tests were carried out on C₃F₇CN/CO₂ mixtures using a rod-plane electrode and subjected to standard lightning impulse (1.2/50 μs). The 50% breakdown voltage, U₅₀, and V-t characteristics were obtained for C₃F₇CN mixtures. Results have demonstrated that increased C₃F₇CN concentrations in the mixture as well as longer electrode gap spacing can increase the breakdown strength of the test gas mixtures. A mixture of 20% C₃F₇CN / 80% CO₂ has shown higher breakdown strength than SF₆ in non-uniform field.

I. INTRODUCTION

Sulphur hexafluoride (SF₆) is widely used as an insulation and an interruption medium for applications such as gas insulated lines and switchgear. Approximately 10,000 tons of SF₆ are being installed annually [1]. The combination of several key properties such as high dielectric strength, good arc quenching capability, low boiling point as well as being chemically inert, non-toxic and non-flammable make it an almost ideal dielectric for high voltage equipment. However, with a global warming potential (GWP) 23,500 [2] times higher than that of CO₂ and an estimated atmospheric lifetime of 3,200 years, SF₆ is considered to be a highly potent greenhouse gas. For this reason, there is an increasing interest from both industries and academics to find a suitable replacement gas with a much lower environmental impact.

Research in SF₆ alternatives has been ongoing for decades and gases such as perfluorocarbons, perfluoroketones and many others have been investigated. However, the task of replacing SF₆ has proven to be challenging as it is difficult to find an ideal substitute that combines all the key properties of SF₆. Two well-known emerging candidates for replacing SF₆ are Novec™ 4710 (C₃F₇CN) [3] and Novec™ 5110 (C₅F₁₀O) [4]. The high boiling point of C₅F₁₀O (27°C) means that it may be difficult to find a C₅F₁₀O mixture with comparable dielectric strength to SF₆ whilst maintaining its gaseous form in compressed gas insulated equipment. As a result, C₃F₇CN is

considered to be a more technically viable solution, especially in high voltage equipment.

This paper investigates the breakdown characteristics of C₃F₇CN in terms of mix ratios and electrode gap distances. The obtained data were then compared to SF₆ data acquired from the literature [5]. V-t characteristics of C₃F₇CN mixtures were also examined for different gas concentrations and electrode gap distances.

II. COMPARISON OF SF₆ AND C₃F₇CN GASES

C₃F₇CN, also known as Novec™ 4710 or 2,3,3,3-tetrafluoro-2-(trifluoromethyl)propanenitrile [(CF₃)₂CFCN], belongs to the fluoronitriles group. C₃F₇CN has several similar properties to SF₆ [3]. Both gases are non-flammable, odourless, colourless and non-ozone depleting.

Table I compares the basic properties of SF₆ and C₃F₇CN. It is noteworthy that the GWP of C₃F₇CN is still reasonably high at 2,100. However, only 4-10% C₃F₇CN is used in the mixture for existing commercial products, which represents a 98% reduction in GWP when compared to SF₆ [1]. The other key difference between the two gases lies in the atmospheric lifetime. While C₃F₇CN can decompose within 30 years, SF₆, due to its long atmospheric lifetime, has an accumulative environmental impact over time.

C₃F₇CN has inherently high dielectric strength. In its pure form, the dielectric strength of C₃F₇CN is approximately double than that of SF₆. However, given the fact that it has a relatively high boiling point (-4.7°C), it has to be used in low concentrations as part of a binary mixture with a diluent gas such as CO₂ or N₂. The literature [3] articulates that C₃F₇CN/CO₂ mixtures have comparably higher breakdown strength than their C₃F₇CN/N₂ counterpart. Therefore, this paper focuses the investigation on C₃F₇CN/CO₂ mixtures.

TABLE I
 COMPARISON OF PROPERTIES FOR C₃F₇CN AND SF₆[2][3]

Property (at 25°C)	C ₃ F ₇ CN	SF ₆
Molecular Weight (g/mol)	195	146
Boiling Point (°C)	-4.7	-63.8
Vapour Pressure [bar (g)]	1.5	20.5
Dielectric Strength at 0 bar (g) [pu to SF ₆]	≈2	1
Atmospheric Lifetime (years)	30	3,200
Global Warming Potential (GWP)	2,100	23,500

III. EXPERIMENTAL SETUP AND PROCEDURE

A. Experimental Setup

A small poly (methyl methacrylate) (PMMA) pressure chamber was fabricated. The pressure chamber was first vacuumed, then filled with the designated gas mixture up to atmospheric pressure (1 bar absolute) and was allowed to settle for an hour prior to testing. The experimental test circuit is shown in Fig. 1.

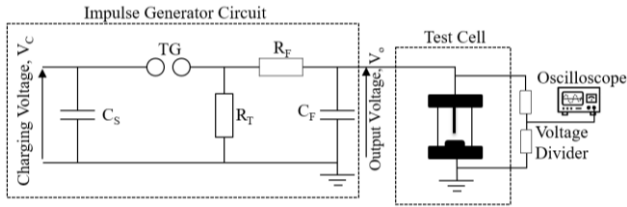


Figure 1. Lightning impulse generator test circuit.

All electrodes were made of brass alloy which is compatible with C_3F_7CN . Rod-plane electrode configuration was used to represent a non-uniform field distribution. The rod electrode tip had a 35° angle while the plane was a Rogowski profile electrode. The electrode gap distance, g , can be adjusted externally from 10 to 30 mm using an adjustable handle on the high voltage electrode side. The lower electrode is always in a fixed position. Prior to a set of experiments, electrodes were firstly polished and then cleaned with acetone to clear the flashover marks from the previous tests. The test cell and electrode dimensions are shown in Fig. 2.

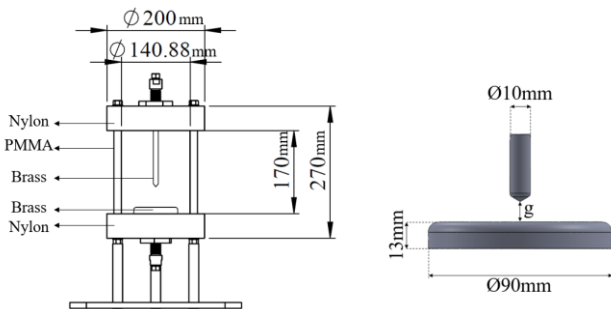


Figure 2. Dimensions of pressure vessel and test electrodes.

B. Experimental Procedure

A standard lightning impulse voltage waveform ($1.2/50 \mu s$) was applied to the high voltage electrode of the test cell. The up-and-down procedure was carried out following the guidance of the BS EN 60060-1:2010 standard [7]. Fig. 3 shows a typical set of tests following the up-and-down procedure. For every test arrangement, a set of 40 impulses was used to determine the 50% breakdown voltage, U_{50} , of the gas mixture. Everytime a gas mixture was refilled, it was observed that the breakdown voltage was rising with the number of impulse applications before reaching a stable up-and-down procedure. This is described in [8] as the conditioning effect, where particles can initiate breakdowns at lower voltages but are later reduced in size and affect the breakdown voltage less. This

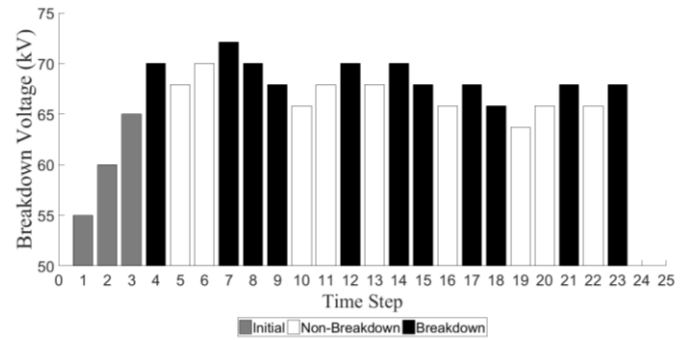


Figure 3. Up-and-down test for 1 cm gap distance, rod-plane, 10% C_3F_7CN / 90% CO_2 mixture.

resulted in having about 15-20 impulses applied to the gas before the official set of 40 impulses. A time interval of 2 minutes was applied between each impulse shot. This allowed the gas mixture to have enough time to recover after a breakdown.

The U_{50} was calculated using the following equation [8]:

$$U_{50} = U_0 + \Delta U \left(\frac{A}{k} \pm \frac{1}{2} \right) \quad (1)$$

where U_0 is the lowest breakdown voltage that has occurred, ΔU is the step voltage, A is the sum of the number of events that occurred at each step and k is the number of rarer events. If the rarer events were breakdowns, the sign would be negative, or in the case of non-breakdowns the sign would be positive.

IV. ELECTRIC FIELD COMPUTATION

COMSOL software was used to compute the electric field distribution of the rod-plane electrode configuration with a 30 mm gap distance, as shown in Fig. 4. By applying the experimental breakdown data, the maximum electric field is located at the rod tip, where the breakdown is most likely to occur. In the experiment, breakdowns mostly occurred at the centre of the plane electrode, which validates the location of E_{max} (kV/mm) in the COMSOL model. Increased electric field can also be seen along the edges of the plane electrode. These edges were rounded to minimise the likelihood of breakdown occurrences along the electrode edge.

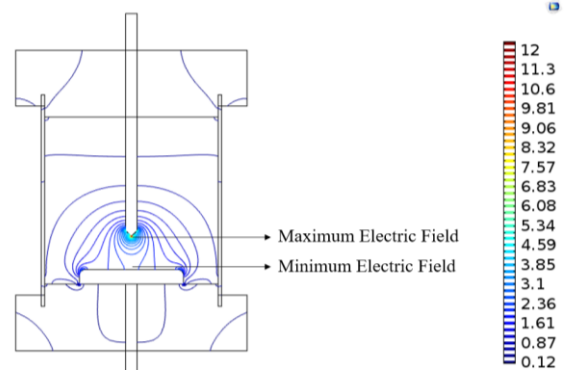


Figure 4. COMSOL simulation for 30 mm gap distance, rod-plane, 10% C_3F_7CN / 90% CO_2 gas mixture.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A. Effect of Gap Distance and Mixture Ratio

From the literature [3][9], it was found that the breakdown voltage of the gas mixture increases with C_3F_7CN content. It can be seen from Fig. 5 that there is a small increase in the breakdown voltage of the gas when the gas changed from 100% CO_2 to a mixture of 10% C_3F_7CN / 90% CO_2 . The breakdown voltage increases significantly when the concentration of C_3F_7CN is increased to 20% C_3F_7CN / 80% CO_2 mixture. The results in Fig. 5 indicate that the experimental tests of this paper are in good agreement with previous investigations [3][9].

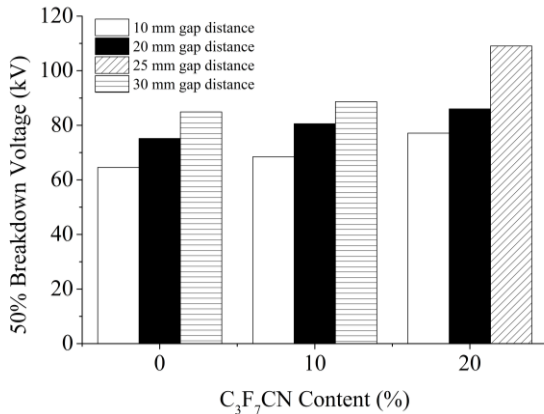


Figure 5. U_{50} as a function of C_3F_7CN content in a rod-plane electrode configuration for different gap distances and positive lightning impulse.

As shown in Fig. 6, as the pressure spacing product (pd) of the gas mixtures increases so does the breakdown voltage. This agrees with Paschen's law which states that after a specific point the breakdown voltage of a gas is approximately proportional to the pressure spacing product. The mixture containing 20% C_3F_7CN concentration demonstrates a slightly better performance to the SF_6 [5] data under positive lightning impulse and non-uniform field. It can also be seen that the rate of increase of both gases is very similar. The increased breakdown voltage of the 20% C_3F_7CN / 80% CO_2 mixture

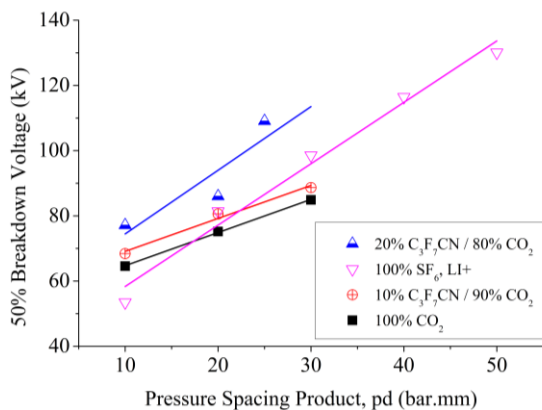


Figure 6. U_{50} as a function of pressure spacing product in a rod-plane electrode configuration comparing C_3F_7CN mixtures to SF_6 under positive lightning impulse.

was expected as Kieffel [6] had found that a ratio of 18% to 20% C_3F_7CN concentration could reach an equivalent breakdown voltage to 100% SF_6 .

The U_{50} for CO_2 and C_3F_7CN gas mixtures are reasonably close at lower values of pd but the difference is more evident at higher values.

B. Breakdown Field Strength

The obtained U_{50} data can be used to determine the maximum breakdown field strength (E_{max}) for each gas mixture as shown in Fig. 7. Equation (2) was developed by Howard [10] to calculate the field strength for non-uniform field electrode configurations:

$$E_{max} = \frac{2U_{50}}{R \ln\left(\frac{4x}{R}\right)} \quad (2)$$

where R is the radius of curvature of the point tip, x is the rod-to-plane gap spacing and U_{50} is the breakdown voltage.

As can be seen in Fig. 7, E_{max} decreases with increasing pd values. The breakdown field strength curves are observed to decrease more gradually at higher pd values. This requires further testing at extended pd range to verify the trend.

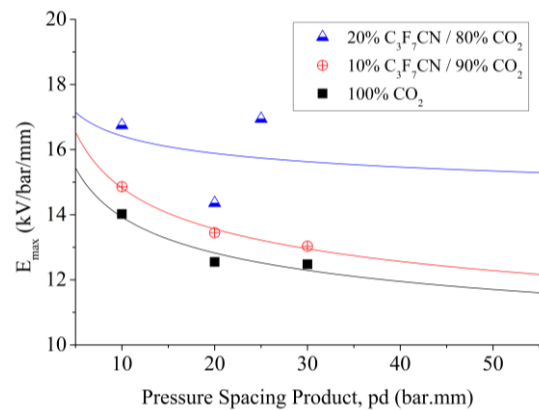


Figure 7. Breakdown field strength as a function of pressure spacing product in non-uniform gaps for different mixtures under positive lightning impulse.

C. Voltage-time Characteristics

V-t characteristics were also examined in this paper. The main pattern observed in Figures 8 and 9 is the V-t curve rising gently in short time regions. One common property of all the V-t curves shown in the two figures is that most of the breakdown times are concentrated in the region below 10 μs with only a few dispersed points exceeding this value.

Fig. 8 compares the V-t characteristics for different C_3F_7CN contents while Fig. 9 illustrates the 10% C_3F_7CN / 90% CO_2 mixture for different gap distances. Based on these results, it was found that there was little difference in average breakdown time when the C_3F_7CN concentration was increased from 10% to 20%. However, the average chopping voltage (the point where the voltage rapidly collapses to zero value during a breakdown) is increased by approximately 10 kV when the

mixture is changed from 10% C_3F_7CN / 90% CO_2 to 20% C_3F_7CN / 80% CO_2 . From Fig. 9, it can be seen that the breakdown voltage times become less dispersed as the gap distance is increased. Most of the breakdown times for the 30 mm gap distance are in the region below 5 μs . This causes the average breakdown time to reduce as the electrode gap spacing is increased. The average chopping voltage is significantly increased with longer gap spacing.

It is unclear if C_3F_7CN concentration and electrode gap distance have a significant correlation to the V-t characteristics based on these initial results. Further study is required to establish a clearer correlation.

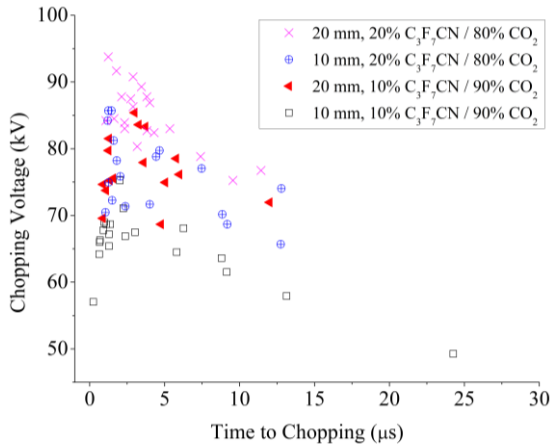


Figure 8. V-t characteristics of C_3F_7CN mixtures under positive lightning impulse.

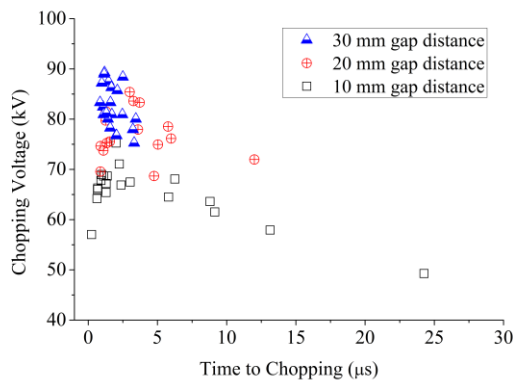


Figure 9. V-t characteristics of 10% C_3F_7CN / 90% CO_2 for different gap distances.

VI. CONCLUSION

This work presents the experimental investigations carried out on C_3F_7CN/CO_2 mixtures as a potential alternative to SF_6 in high voltage equipment. Experiments were conducted using a rod-plane electrode configuration with varying conditions such as gap spacing and mixture ratio. All the experiments were carried out using standard lightning impulse voltage (1.2/50 μs) of positive polarity. Initial results have shown that

increased C_3F_7CN concentration and gap spacing can increase the breakdown voltage of the gas mixture. The mixture of 20% C_3F_7CN / 80% CO_2 proved to have a higher breakdown voltage compared to 100% CO_2 and 10% C_3F_7CN / 90% CO_2 . The same mixture has shown higher breakdown performance than SF_6 under non-uniform field and positive LI. This, however, was not a direct comparison since the SF_6 data was extracted from the literature. Further testing is necessary in the future to investigate C_3F_7CN and the effect that conditions such as field uniformity and pressure have on the dielectric strength of the gas. Results in this paper have shown that C_3F_7CN can be a promising candidate to replace SF_6 gas in high voltage applications.

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