EXPERIMENTAL INVESTIGATION OF CF_3I-CO_2 GAS MIXTURES UNDER LIGHTNING IMPULSES

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ABSTRACT

This paper describes sparkover characteristics of CF_3I-CO_2 gas mixture, with focus on 30%-70% mixture. Standard lightning impulse of 1.2/50 is used in this study, along with three different electrode configurations with variable gap lengths. It is found that higher gap lengths provides higher U_{50} and E_{max} for a given electrode configuration, although the rise in U_{50} is more obvious in sphere-sphere configuration, due to more uniform electric field. Breakdown strength also increases with gas pressure, with tests being carried out up to 2 bar (abs). An increase in CF_3I content in CF_3I-CO_2 gas mixture also provides an increase in insulation strength. As in gas pressure, effects in CF_3I content are more obvious under more uniform electric field conditions. Solid by-product of the gas mixture has been identified as iodine, taking as much as 54% of the total weight of all by-products.

1. INTRODUCTION

In electricity networks, some of the high voltage applications make use of sulphur hexafluoride (SF_6) gas as an insulation medium. However, many studies show that SF_6 greenhouse effects raise concerns to its environmental impact [1]. In addition, SF_6 also has an extremely long atmospheric lifetime, resulting in an accumulation in the atmosphere once released [1].

Until recently, researchers have been trying to find suitable alternatives for SF_6. Gases and gas mixtures, especially those containing carbon (C) and fluorine (F), can have better dielectric strength than SF_6. Some perfluorocarbons and related mixtures show breakdown strengths as high as 2.5 times that of SF_6, but these are also greenhouse gases [2]. One of the candidates is trifluoroiodomethane (CF_3I). Due to its high boiling point property, CF_3I gas is mixed with other gases such as CO_2 and N_2 to provide a more practical way of deploying it as an insulation medium. In this work, tests were carried out for CF_3I-CO_2 gas mixtures. Based on reports from previous works [3], CF_3I-CO_2 gas mixtures with a ratio of 30% of CF_3I and 70% of CO_2 have been chosen as the main gas mixtures to be investigated in this paper.

2. EXPERIMENTAL SETUP

2.1 Lightning Impulse Generation

A 400 kV Haefely impulse generator was used to generate the lightning impulse shape. A 50ns risetime capacitive divider was used to measure the impulse voltage, and a digital storage oscilloscope was used to record the waveform.

2.2 CF_3I gas removal system

A gas removal system is used in the experimental setup, so that no gas will be released into the atmosphere. After each test, the gas was stored in purpose-designated gas cylinders.

2.3 Electrode configuration

There are three main electrode configurations used in this study, namely plane-plane, rod-plane and sphere-sphere. The spheres have diameters of 50 mm and the rod electrode has a tip diameter of 1 mm. These electrodes are made from brass, and their surfaces are mirror finished. In the tested electrodes, all high voltage electrodes are stationary; while the ground electrodes are vertically moveable, so that a desired gap length can be achieved. For the same gap length of 1 cm, and for the same voltage of 1 kV, the field utilization factor for each electrode configuration is given in Table 1.

Table 1: Field utilization factor of test electrode configurations

Electrode configuration	Field utilization factor
Rod-plane	0.120
Plane-plane	0.763
Sphere-sphere	0.870

3. MEASUREMENTS TECHNIQUES

3.1 50% Breakdown Voltage (U_{50})

For this test, U_{50} for CF_3I-CO_2 gas mixtures are obtained as according to the Standard [4]. The up-and-down method is used to determine U_{50} by applying at least 20 impulse shots at a timed interval of 120 seconds.

3.2 Voltage-time Characteristics

Another characteristic used to evaluate the insulation performance of the gas mixtures, is the voltage-time (*V-t*) characteristic which represents the relationship between the breakdown voltage and time to breakdown. Since the voltage used in this study is a standard lightning impulse waveform, the breakdown can occur before, after, or at the peak value. The value of voltage when the breakdown occurs and its associated time lag are recorded and used to plot the *V-t* characteristics.

4. EXPERIMENTAL RESULTS

This section reports on the results obtained from laboratory tests on CF_3I-CO_2 gas mixtures. These results are presented for CF_3I-CO_2 gas mixture with a ratio of 30-70% at 1 bar (abs) pressure.

4.1 Effects of Electrode Configuration and Impulse Polarity

In this test, the electrode gap length, *g*, is selected to be 1 cm, in order to observe only the effects of lightning impulse polarity, as well as the electrode configuration effects. All the values of U_{50} are used in electric field computations to determine the corresponding maximum electric field (E_{max}) that would appear prior to breakdown. As can be seen in Fig**.** Fig. 1, there is a little difference in U_{50} values with positive and negative impulse polarities. This is mainly because the gap length is only 1 cm. A bigger gap length may show a bigger difference in U_{50} as will be reported in the next section; bigger gap lengths have more non-uniform electric field distributions between the electrodes. The differences for E_{max} appear are at 1.45% increase for rod-plane, 2.7% decrease for plane-plane and 6.34% decrease for sphere-sphere from positive to negative polarity.

As can be seen in Fig. 2, the *V-t* characteristic for a rod-plane configuration under a positive impulse is concentrated around very short times, less than 2 µs, i.e. most breakdowns occur around the peak for the lightning impulse. Most of the measured *V-t* characteristics have almost flat curves which is in agreement with other independent results by Takuma [5]and Hoshima et al. [6].

4.2 Effects of Gap Length

The gap length for each electrode configuration is varied to investigate its on the breakdown strength of CF_3I-CO_2 gas. As can be seen on Fig. 3, under both positive and negative lightning impulse polarities, E_{max} is less affected by gap length when compared to U_{50}, with an exception to rod-plane configuration under negative impulses in which E_{max} increases significantly with gap length. In the sphere-sphere configuration, an increase of 50% in gap length produces an increase of 31% in U_{50} under a positive impulse and 29% under negative impulse polarity.

Although the rod-plane configuration has the highest E_{max} values, the U_{50} under positive impulse, it is the least affected by gap length. This study shows that the mechanism of breakdown is less dependent on gap length, as has been discussed by Nierneyer et al. [7] where several leader channel development in electronegative gases can be achieved with different electrode configurations.

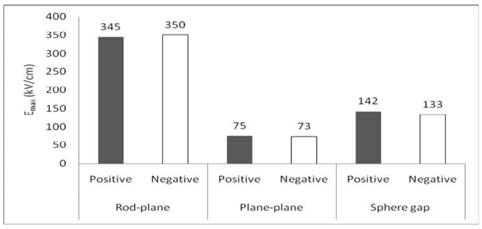


Fig. 1 Effects of electrode configuration on E_{max} for CF_3I-CO_2 gas mixture at 1 cm gap

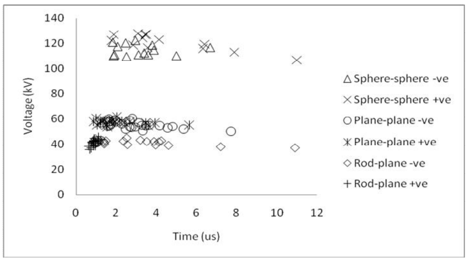
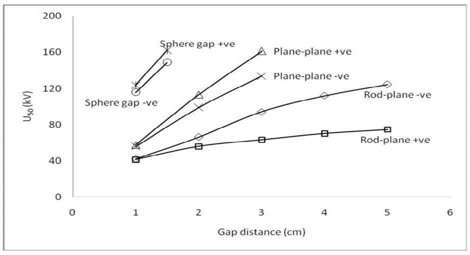
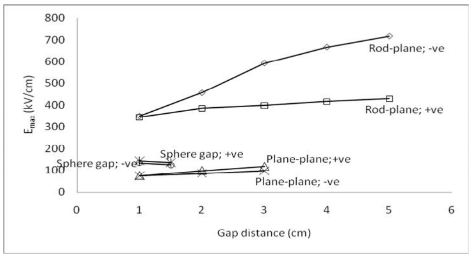


Fig. 2 V-t characteristics for various electrode configurations; 1 cm gap



(a) U_{50}



(b) E_{max}

Fig 3 Effect of gap length on breakdown voltage

4.3 Effects of Gas Pressure

The pressure of CF_3I-CO_2 (30%-70%) gas mixture is increased from 1.0 bar (abs) to 1.5 bar (abs) and 2.0 bar (abs). Only the rod-plane electrode configuration is used in this study, with gap lengths from 1 cm to 5 cm. The results are shown in Fig. 4. The measurements also showed that higher pressure produces higher *V-t* characteristics for CF_3I-CO_2 gas mixtures. As has been reported by Yoshida et al. [8], *V-t* characteristics for various pressures of SF_6 under lightning impulse become higher as the gas pressure increases.

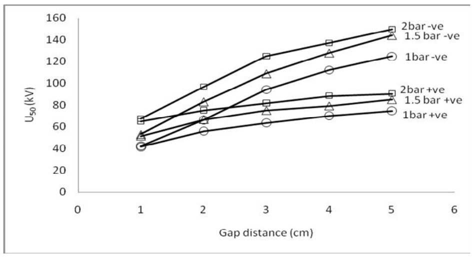


Fig. 4 Effects of gas pressure on breakdown voltage

4.4 Effects of CF_3I content

It should be emphasized that the selection of CF_3I content is dependent on three major factors: insulation strength, boiling point and the by-products of the gas mixture. Although an increase in CF_3I content might increase the insulation strength, the boiling point and by-products will also be increased, which is an undesirable outcome. This particular study is carried out with rod-plane and plane-plane electrode configurations, with maximum gap length of 5 cm and 3 cm, respectively. The pressure is fixed at 1.0 bar (abs). Fig. 5 shows the results for U_{50}.

From these results, it can be said that, in a rod-plane electrode configuration, the CF_3I content in a gas mixture of CF_3I-CO_2 will have more effect for smaller gaps, as compared to larger gaps, under both positive and negative impulse polarities. On the other hand, with plane-plane electrode configuration, a 20% increase in CF_3I content gives almost a similar increase in U_{50} under positive impulse polarity, in the range of 20%-22%.

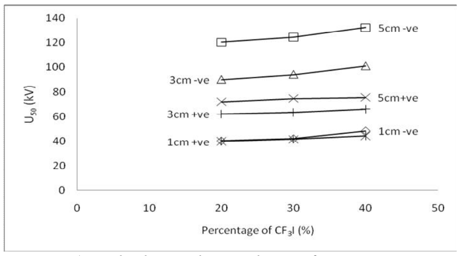
Effects of CF_3I content in CF_3I-N_2 and CF_3I-Air gas mixtures have been studied by Toyota et al. [9] using steep-front square voltage. It is reported that *V-t* characteristics for CF_3I-N_2 and CF_3I-Air mixtures increase with CF_3I content.

4.5 Investigation of Breakdown Solid By-Products

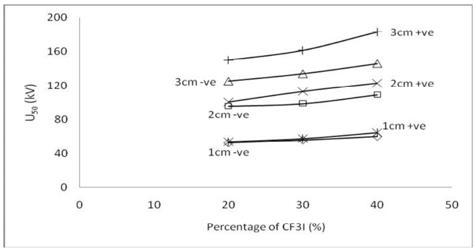
Following breakdown, there are two categories of by-products of CF_3I-CO_2 gas mixtures; solid and gaseous by-products. The gaseous by-products have been reported [10-13] they mostly come from C_2F_6 gas (hexafluoroethane). The solid by-products, brownish material has been identified as iodine [11,14,15].

In this investigation, two samples of electrodes, the rod electrode and plane (ground) electrode have been studied to examine the solid by-products. Fig. 6 shows the brownish area on each electrode.

Image magnification using Scanning Electron Microscope (SEM) and element analysis using Energy Dispersive X-Ray (EDX) are used to analyse the solid by-products deposited on the electrodes. Table 2 shows the element analysis results for the rod electrode. Both rod and plane electrodes contain iodine as the main element. More iodine is deposited on the rod electrode, contributing as much as 53.8% of the overall weight, while on a plane electrode, iodine is contributing 41.7%. If there is a solid dielectric between the high voltage electrode and ground electrode, iodine may deposit on the surface of that dielectric and will significantly affect the insulation strength of CF_3I gas mixture, as reported in [11,14].



a) rod-plane electrode configuration



b) plane-plane electrode configuration

Fig. 5 Effect of CF_3I content on breakdown voltage under positive and negative impulse polarities

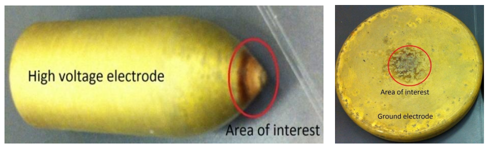


Fig. 6 Solid by-product on rod and plane electrodes

Table 2 Element analysis using EDX on rod electrode

Element	Weight (%)	Atomic (%)
Carbon (C)	6.62	22.11
Oxygen (O)	13.54	33.98
Fluorine (F)	6.80	14.37
Chlorine (Cl)	0.48	0.54
Potassium (K)	0.53	0.54
Iron (Fe)	0.81	0.59
Copper (Cu)	9.73	6.15
Zinc (Zn)	7.69	4.72
Iodine (I)	53.80	17.01
Total	100	100

5. CONCLUSION

The breakdown characteristics of CF_3I-CO_2 gas mixtures were investigated under different electrode and laboratory test conditions. As expected, breakdown under negative polarity lightning impulse were much higher in very non-uniform electric fields compared with those under positive polarity. Generally, larger gap lengths have proportionally higher U_{50}, and thus higher E_{max}. In this study, the highest breakdown level occurred in sphere-sphere configuration and a small increase in gap length provided a significant increase in U_{50} values. The *V-t* characteristics showed that under a positive impulse, in a small gap rod-plane configuration, most of the breakdown occurred very early. It is thought that this is due to the appearance of leader discharges within small gaps.

It was also found that an increase in pressure would increase the breakdown strength of the gas mixture. Although the insulation strength of the CF_3I-CO_2 gas mixtures was increased with CF_3I content, there was no significant effect for the case of the rod-plane configuration under positive impulse, as compared with plane-plane configuration. This could be attributed to the fact that CF_3I performs better under a more uniform field stress.

An investigation into the breakdown solid by-products revealed iodine as the main solid by-product of the electrical discharge in CF_3I-CO_2 gas mixture. Upon closer microscopic observations, more iodine was found to be deposited on the high voltage electrodes. It is possible that this may contribute to a decrease CF_3I insulation property.

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