EXPERIMENTAL INVESTIGATION OF CF_3I-CO_2 GAS MIXTURES ON THE BREAKDOWN CHARACTERISTICS IN UNIFORM AND NON-UNIFORM FIELD CONFIGURATIONS

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By

MUHAMMAD SAUFI KAMARUDIN

School of Engineering
Cardiff University

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SUMMARY

This thesis is concerned with the investigation of trifluoroiodomethane (CF_3I) gas mixtures as an alternative for an insulation medium in high voltage applications. The work has involved a broad review of literature, followed by developing a test rig for carrying out experimental investigations, extensive computational modelling and simulation studies as well as extensive laboratory tests on CF_3I gas and its gas mixtures.

The literature survey reviewed the current trend of efforts taken by researchers to find solutions for minimizing the usage of sulphur hexafluoride (SF_6) as a gas insulator, focusing on CF_3I and its mixtures. The physical properties of CF_3I are investigated, along with thermal and electrical properties.

A new test rig has been designed and constructed specifically to be used for gas insulation research. The test rig is integrated with wireless temperature and humidity sensors, as well as an electrode gap length control system. The test rig is completed with a gas recovery system to ensure proper gas handling is carried out after each test.

Extensive laboratory experimental investigations on CF_3I mixtures have been completed, focusing on the mixture of CF_3I-CO_2 gas with a ratio of 30%-70%. Standard lightning impulse of 1.2/50 has been used, with both positive and negative polarity. The effects of electrode configuration, impulse polarity, electrode gap length, gas pressure, and CF_3I content have been investigated. Insulation properties such as 50% breakdown voltage (U_{50}) and *V-t* characteristics for each test condition are investigated and presented, as well as the electric field behaviour. Finite element method (FEM) has been used to determine the electric field behaviour of a given test condition. This study revealed that CF_3I gas mixtures perform better under more uniform field condition. It was also found that an increase in gas pressure will increase the insulation strength and an increase in CF_3I content is more likely to give benefit in conditions with a more uniform field when compared to less uniform field conditions. Also, relation between liquefaction temperatures of a CF_3I-CO_2 mixture with varying CF_3I content has been developed for various pressures based on literature.

Observations on solid by-products of CF_3I have also been carried out. It has been found that iodine particles are deposited on both high voltage and ground electrodes, which can affect the insulation properties of CF_3I and its mixtures.

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CHAPTER 1: INTRODUCTION

1.1 Background

The electrical power supply plays such an important role in today's modernized world that the quality and continuity of supply is of highest priority. Power producers have put enormous effort into ensuring demand for electricity is securely and reliably delivered to customers, ranging from a small power outlet in a house to a large processing plant. From the consumer's perspective, any interruptions to the electrical supply could be problematic, be it a blackout, voltage dip, or overvoltage that could contribute to loss of equipment, or disruption of service. In fact this could directly impact the economy as a whole, if on a large enough scale.

In a typical power system, there are three major parts, these include generation, transmission, and distribution of electricity. During generation, other sources of energy, such as wind, solar, water, and even nuclear, are converted into electrical power. The power is then transmitted in bulk by means of overhead lines or underground cables at a variety of levels which depend on the power generated, distance of transmission, loads condition at the end part and other factors. Voltage is typically increased significantly prior to transmission in order to reduce losses. The final stage of the delivery of electricity is distribution. Distribution usually involves a network of substations, again depending on the consumers' needs, these will be in different levels of rating. Figure 1.1 below shows an example of such system.

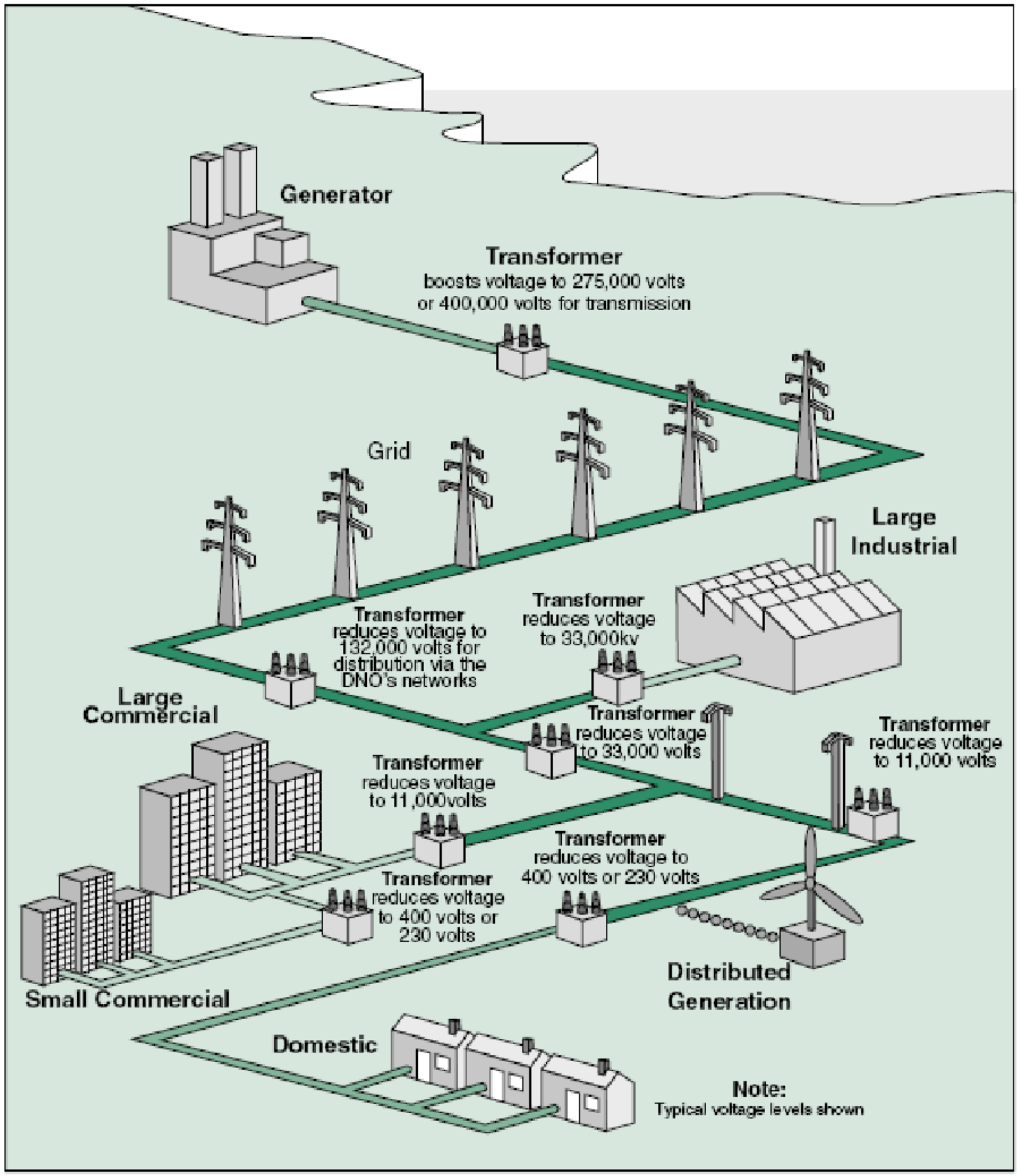


Figure 1.1: Simplified UK electrical power transmission system [1]

In an electricity network, some of the high voltage applications make use of sulphur hexafluoride (SF_6) gas as an insulation medium, such as in the gas insulated transmission line (GIL), gas insulated switchgear (GIS), and gas circuit breaker (GCB). Due to its superior insulation properties, SF_6 has been the primary insulator for many high end electrical applications. However, many studies show that SF_6 greenhouse effects raise concerns to its environmental impact. There are three major types of global warming potential (GWP) gases: these are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and SF_6. In addition to having high GWPs, SF_6 and PFCs have an extremely long atmospheric lifetime, resulting in an accumulation in the atmosphere once released [2]. Some of the studies in the awareness of the hazard caused by SF_6 have been well described in the following statements:

"SF_6 is a strong greenhouse gas and the molecule is very resistant against attack in the atmosphere. The natural self cleansing property of the atmosphere is insufficient to deal with such super molecules. Its production is now restricted under the Kyoto Protocol." [3]

"Sulfur hexafluoride is the most potent greenhouse gas in existence. With a global warming potential 23,900 times greater than carbon dioxide, one pound of SF_6 has the same global warming impact of 11 tons of carbon dioxide." [4]

"The atmospheric lifetime of SF_6 is 3,200 years, which results in essentially irreversible heat trapping within the atmosphere." [5]

Takuma et al [6] stated in a report that although emission of SF_6 is relatively small compared to CO_2, the global warming potential (GWP) is the highest of all available gases. For that reason, the electrical power industry has been working hard to find a replacement for SF_6 with a smaller GWP and less environmental impact. In fact, Schneider Electric has introduced the Premset switchgear [7] and Mitsubishi Electric has introduced the Dry Air Insulated Switchgear [8] to be used in medium voltage distribution which are free from SF_6.

Until recently, researchers have been trying to find suitable alternatives for SF_6. Gases and gas mixtures, especially the ones containing carbon (C) and fluorine (F), can have better dielectric strength than SF_6. Some perfluorocarbons and related mixtures are showing breakdown strengths as high as 2.5 times that of SF_6, but these are also greenhouse gases [9]. One of the very promising 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, since CO_2 and N_2 have lower boiling temperatures.

1.2 Direction of Research and Objectives

The focus of this study is to provide a fundamental knowledge on the breakdown properties of CF_3I and its mixtures under lightning impulses. As mentioned earlier, it is fairly important to search for good prospective insulation gases in order to find an alternative for SF_6. U_{50} and *V-t* characteristics properties will offer an insight into how well the CF_3I gas mixtures behave as an insulation medium.

For the tests to be carried out successfully, a reliable experimental setup needs to be developed. This consisted of an air-tight pressure vessel, with all the security measures, fittings, and assemblies fitted, as well as generation and measurement of the lightning impulse, and the data acquisition of the test results. A reliable gap length control is particularly important. The entire available electrodes configuration should not disturb the gas mixtures inside the vessel.

A simulation technique is needed to determine the electrical field for any given test condition. This will ensure a full understanding of the level of the maximum electric field that the CF_3I gas mixtures can handle, and to provide better insight into actual performance under electric field behaviour. The specific objectives of this study are outlined below:

i. To review current knowledge and trends in research interests related to this study, which include alternative gases for SF_6, determination of the electric field effects, factors affecting breakdown of gases, and measurement techniques in high voltage testing;

ii. To build a novel pressure vessel as part of the test rig design and construction, with consideration given on the size, gas recovery system, gap control system, safety measures, and reliability of the vessel;

iii. To investigate the breakdown properties of CF_3I-CO_2 mixtures under lightning impulse and several factors, such as electrode configurations, polarity of lightning impulse, gap length between electrodes, pressures and CF_3I content. The gap length is limited to 5cm while the maximum lightning impulse that can be applied is limited to around 170 kV in order to protect the HV bushing of the pressure vessel; and

iv. To examine the electric field for each given test condition using an adequate model in simulation software.

1.3 Contribution of Thesis

The following contributions were achieved during this research programme:

i. Extensive literature search on CF_3I properties and its potential for high voltage applications.

ii. Designed and constructed a pressurised test chamber equipped with measurement and control apparatus, including CF_3I gas recycling.

iii. Conducted extensive tests and collected data on CF_3I gas and its mixtures which allows better understanding of breakdown properties and dielectric strength.

iv. Uniform and non-uniform field properties of the CF_3I gas and its mixtures were clarified and the effect of CF_3I content was quantified

v. Microscopic analysis of breakdown by-products was achieved.

1.4 Organization of Thesis

This thesis is divided into seven chapters:

CHAPTER 2 provides an extensive review of published literature with regard to the study undertaken. A general overview of CF_3I gas and its mixtures are presented along with previous investigations by other researchers for numerous possible mixtures, such as CF_3I-air, CF_3I-N_2, and CF_3I-CO_2, with comparison to SF_6.

CHAPTER 3 presents the development of the test rig design and construction. A detailed explanation of the construction of the pressure vessel is presented. It includes all the considerations related to fittings and assemblies, such as material, pressure relief valve, gauges, linear actuator, and other equipment. This chapter aims to give an overview of the constructed gas evacuation and filling systems as well as how the system is being assembled and operated for mixing gases.

CHAPTER 4 reports investigation and calibration tests and results related to air breakdown. Some fundamental tests with air have been carried out to verify that the test rig is working properly and as means of calibration so that it can be used for further tests with CF_3I gas mixtures. Tests were carried out according to available standards, to determine the U_{50} and *V-t* characteristics for different pressures. This chapter also presents the simulation studies undertaken with detailed explanation on the modelling to be used in numerical simulations.

CHAPTER 5 investigates the breakdown properties of CF_3I mixtures under lightning impulses. In this chapter, focus is given to CF_3I-CO_2 mixtures with a ratio of 30%-70%. Tests were carried out to investigate the effects of three electrode configurations, which are rod-plane, plane-plane, and sphere gap. The CF_3I-CO_2

mixture was subjected to both positive and negative lightning impulses. Also, the effect of gap length was investigated. Based on U_{50} results for a given test parameter, the electric field curves were determined to clarify the effect of electric field on breakdown of the gas.

CHAPTER 6, on the other hand, investigates the breakdown properties of CF_3I-CO_2 mixtures under lightning impulses for different ratios of CF_3I content apart from 30%-70%; these include 40%-60% and 20%-80%. These results will offer insight on how much influence the CF_3I gas has in terms of dielectric strength if it is mixed with CO_2. In addition, the effect of pressure was investigated. CF_3I-CO_2 mixture with a ratio of 30%-70% was tested for up to 2 bars in a rod-plane gap with variable lengths.

CHAPTER 7 presents overall conclusions based on results and findings in this study and outlines recommendations for future investigations.

CHAPTER 2: CF_3I MIXTURES AS SF_6 ALTERNATIVE: A REVIEW

2.1 *Introduction*

Recent developments in the search for alternative gases to replace SF_6 gas throughout the electrical power industry have triggered numerous investigations on SF_6 mixtures, other gases, and mixtures of gases. This is in terms of fundamental characteristics of insulation such as breakdown strength, voltage-time (V-t) characteristics, partial discharge properties, fault interruption capability and others. Although many experimental works and tests have been carried out and presented by researchers [10], [11], [12], [13], [14], [15], there are still gaps that needed to be filled in order to convince the working committee to make a decision to replace SF_6 in high voltage applications.

The aim of this chapter is to provide a comprehensive review of the studies related to the research programme in order to provide a good understanding of one of the prospective gases in replacing SF_6 gas as an insulation medium. These include several factors including insulation characteristics, environmental properties, types of gas mixtures, and overall stability. A good understanding of these factors is vital in determining the implications and the protective performance of the gas mixtures.

2.2 *Sulphur Hexafluoride (SF_6) as an Insulation Gas*

Air is known as a preferred gas insulating medium in the electrical power system, but for more specific applications, such as gas insulated substations and circuit breakers, sulphur hexafluoride (SF_6) has been widely used. SF_6 is regarded as the best gas insulation medium known in high voltage applications [6]. As indicated in the previous chapter, SF_6 is a greenhouse gas and many investigations have been carried out to find an adequate replacement [16].

Although SF_6 is colourless, odourless, and tasteless, its weight is approximately five times heavier than air. Since SF_6 is heavier than air, it tends to pool in low places, so there is a danger of suffocation through oxygen displacement. If the oxygen content in air is reduced to less than 13 percent from the normal 20 percent, nausea and drowsiness can occur [17].

When electrical discharges occur in equipment filled with SF_6, toxic by-products can be produced. These by-products are a threat to the health of workers that come in contact with the by-products. There are four types of electric discharges which will lead to decomposition of SF_6 [18]:

i. partial corona discharges,
ii. spark discharges,
iii. switching arcs, and
iv. failure arcs.

SF_6 by-products, for examples gases such as hydrogen fluoride (HF), sulfuryl fluoride (SO_2F_2), silicon tetrafluoride (SiF_4) and sulphur dioxide (SO_2), are very irritating to the eyes, nose, and throat [19]. James et. al. [20] reported that two workers collapsed after entering an SF_6 storage tower. One of the workers suffered pulmonary edema (excess collection of water fluid in the lungs) for three days. SF_6 and SO_2F_2 were then detected at the area and both exceeded the threshold limit value (TLV).

CF_3I, on the other hand, has been used in fire extinguishing systems [21]. Just as SF_6, CF_3I is also colourless, odourless, and electrically a non-conductive gas. In 1994, Moore et. al. [22] prepared a report to illustrate the conclusion of several studies in order to replace Halon with CF_3I as a fire extinguisher. The report was based on a wide number of publications that focused on the following areas:

i. fire suppression characteristics,

ii. global environmental characteristics,

iii. toxicology information,

iv. stability for temperatures below 116 ºC in the absence of light, oxygen, and water, and

v. compatibility with other materials

It is reported that based on the toxicological, environmental, and fire fighting results for unoccupied areas and streaming applications, CF_3I was selected as a very good candidate to be used as Halon replacement, and this includes Halon 1301 and Halon 1211.

2.3 Properties Required for Power System Applications

In this section, several general characteristics for SF_6 replacement are provided for circuit breakers, gas-insulated transmission lines, and power transformers [23].

2.3.1 Circuit breaker applications

The most important physical characteristics of an insulating gas in circuit breakers (CBs) are related to the electric arc. The characteristics required for arc interruption are high dielectric strength, high interruption capability, which consist of high thermal conductivity and high electron attachment, quick gas recovery and the ability to re-form (self-healing).

2.3.2 Gas-insulated transmission lines (GIL) applications

The properties required for gas-insulated transmission line applications are different from the applications in circuit breakers. Important properties that the adopted gas needs to fulfil are high dielectric strength, long term stability, inertness and good thermal conductivity.

In particular, the gas needs to show a high dielectric strength under different stress conditions, such as uniform and non-uniform fields, electrode roughness and possible presence of conducting particles, and various geometric configurations. Although SF_6 is a good gas dielectric, its stability in non-uniform field is not as good as in uniform field, and this is a major issue [24].

There should be no possibility of chemical reaction within the electrode materials or the metallic structure and the sealing-materials in long-term use (40 years or more). There should also be no contaminations due to deposits, such as carbon deposits, polymerization, or decomposition. Other important characteristics connected to maintenance include being easily removable, having non-harmful by-products, and creating no hazards for personnel or structure, including no risk of fire, explosion, toxicity or corrosion.

2.3.3 Gas-insulated transformers applications

High rating power transformers use oils as dielectric and cooling media. However, several problems in the use of oil exist. The risk of ignition in the presence of air, breakdown due to contamination particles, and ion accumulation are all possible in insulation oils. The adoption of a gas instead of an oil can offer several advantages, such as lower risk of ignition and explosion, reduced weight of the machine and reduced noise overall (gas transmits less vibration than oil).

The properties that a gas should offer to be used successfully in power transformers are high dielectric strength at high pressure (e.g. 500 kPa), low toxicity, inertness, good thermal stability, no risk of fire, fire suppressor, high cooling capability, no reaction with various solid materials, good partial discharge characteristic, wide operative temperature range, easy to handle, a large amount available on the market and low price. Another important property is low boiling point, so that the gas will not liquefy at low temperature conditions, such as during winter time.

2.4 Physical and Chemical Properties of CF_3I

CF_3I is found to have attractive insulation properties. It is known with various names in industry. The most common synonyms for trifluoroiodomethane (CF_3I) include [25]:

- Iodotrifluoromethane,
- Trifluoromethyl Iodide, and
- Perfluoromethyl iodide.

The 3D molecular drawing for CF_3I is shown in Figure 2.1.

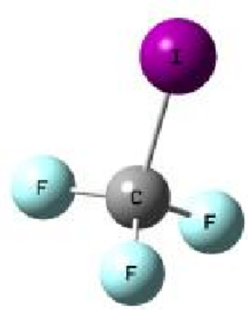


Figure 2.1: 3D molecular drawing of CF_3I, showing three fluorine atoms (light blue) and an iodine atom (purple) connected to a carbon atom (grey) [26]

CF_3I can be identified in the international databases using the following numbers:

- Chemical Abstracts Service (CAS) Number 2134-97-8 or
- European Chemical (EC) Number 219-014-5

Table 2.1 shows the physical properties of CF_3I.

Table 2.1: Physical properties of CF_3I [27]

Physical or Chemistry Property	Value or Description
Molecular weight	195.1
Physical state at 20°C	Gas
Melting point	– 110°C (– 166°F)
Boiling point at 1 atm	– 22.5°C (– 8.5°F)
Liquid density at – 32.5°C	2.36 g/mL
Odour threshold	Odourless
Solubility in water	Slight
Vapour pressure at 25°C	78.4 psia
Pressure-temperature curve	log psia = 5.7411-1146.82/T/K
Critical pressure	586 psia (estimated)
Critical temperature	122°C (estimated)
Critical volume	225 cm^3/mole (estimated)
Electron affinity	150 ± 20 kJ/mole
Vapour heat capacity	16.9 cal/mole-K
C-I bond dissociation energy	54 kcal/mole
Vapour density (air = 1)	6.9

As discussed in Chapter 1 (*Introduction*), one of the main reasons for researchers to search for an alternative gas to replace SF_6 is due to the concern about the SF_6 greenhouse effects. The global warming potential (GWP) of SF_6 is so high that its production has been restricted under Kyoto Protocol [28]. CF_3I, on the other hand, has a very low GWP. Table 2.2 below shows a comparison between CO_2, SF_6, and CF_3I in terms of environmental attributes.

Table 2.2: Lifetimes, radiative efficiencies and direct GWPs relative to CO_2 [29]

Gas	Life time (years)	Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$)	GWP for given time horizon (years)		
			20	**100**	**500**
CO_2	N/A	1.4×10^{-5}	1	1	1
SF_6	3200	0.52	16300	22800	32600
CF_3I	0.005	0.23	1	0.4	0.1

In order to replace SF_6 with CF_3I successfully several physical characteristics need to be investigated. The first property that must be fulfilled is that of a high dielectric strength. The dielectric strength of the selected gas needs to offer a higher value than air and the same order of SF_6 in order to use the same design applied in current GIS systems. A comparative list with dielectric strength of various gases expressed as relative value to SF_6 is shown in Table 2.3:

Table 2.3: Breakdown strengths of selected gases relative to SF_6 [23], [30]

Gas	Relative strength to SF_6	Electron attaching
$C\text{-}C_6F_{12}$	≈2.4	Very strong or strong
C_4F_6	≈2.3	
$C\text{-}C_4F_6$	≈1.7	
$C\text{-}C_4F_8$	1.3	
CF_3I	1.21 (107.7 kV/cm)	
SF_6	1.0 (89 kV/cm)	
C_3F_8	0.9	
CO	0.4	Weak
N_2O	0.44	
CO_2	0.3	
Air	≈0.3	
N_2	0.36	Non-attaching
H_2	0.18	

2.4.1 Electron Interaction Properties

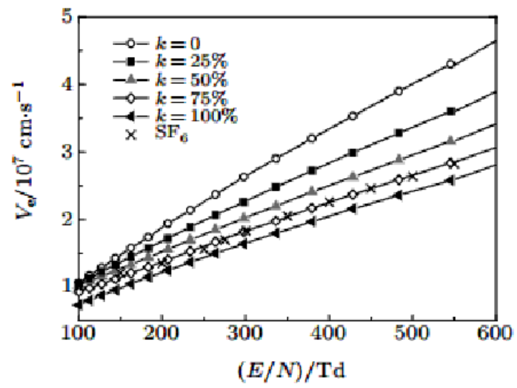
It has been reported in [23] that in order to present good dielectric strength, the gas should present with the ability to reduce the number of free electrons. Therefore the following properties need to be considered:

- electron attachment or electronegative property for removing free electrons by attachment;
- the ionization cross section should present a low value in order to offer a reduced number of free electrons;
- electron slowing-down properties should allow a slowdown of electrons in order to facilitate their capture at lower energy; and
- the electron impact ionization should have a high value as it prevents the ionization by electron impact.

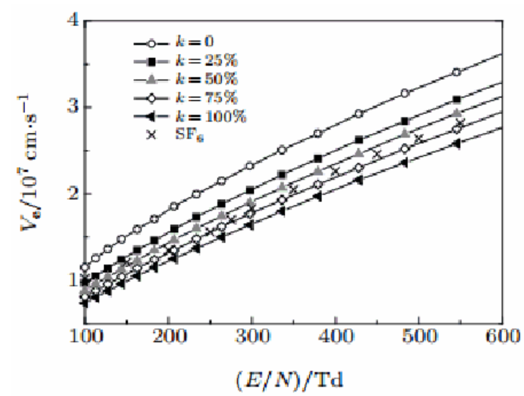
De Urquijo et al. [31], [32], [33] as well as Deng and Xiao [34] have determined electron interaction properties of CF_3I, CF_3I-N_2 and CF_3I-CO_2 mixtures using a pulse Townsend experiment and Boltzmann equation analysis. In particular, the electron drift velocity v_e, the effective ionization coefficient $(\alpha-\eta)/N$, and the limiting field strength E/N_{lim} for CF_3I and its mixture with N_2 and CO_2 at different percentages were published. In these properties, α is electron impact ionization coefficient, η is the attachment coefficent, E is the electric field and N is the gas density.

2.4.1.1 Electron Drift Velocity, v_e

Figure 2.2 depicts the electron drift velocities for CF_3I-N_2 and CF_3I-CO_2 for various levels of pressure in comparison with SF_6.



(a) CF_3I-N_2



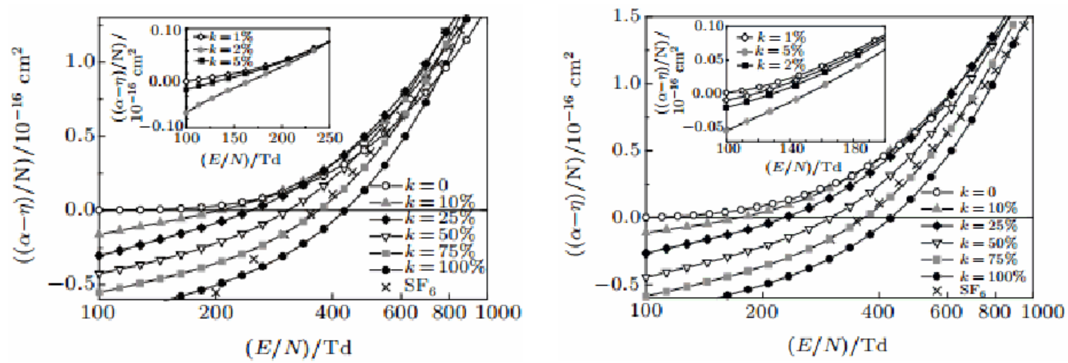
(b) CF_3I-CO_2

Figure 2.2: Electron drift velocities as a function of E/N at different CF_3I ratio *k* in comparison with SF_6 [34]

It is clear that the electron drift velocity (v_e) decreases as the CF_3I content increases for both gas mixtures, as expected with an electronegative gas as in CF_3I. The v_e for CF_3I-N_2 mixtures of 75%-25% gives the same value with those of SF_6. Using the same mixture ratio, CF_3I-CO_2 gives slightly lower v_e than SF_6.

2.4.1.2 Effective Ionization Coefficient, (α-η)/N

The density-normalized effective ionization coefficient (α-η)/N, calculated by Deng and Xiao [34], indicates that (α-η)/N increases when E/N increases for both CF_3I-N_2 and CF_3I-CO_2 gas mixtures, as shown in Figure 2.3. Interestingly, for CF_3I-N_2 mixtures, where E/N is more than 300 Td, the increment of (α-η)/N for the mixtures tends to be higher than that of pure N_2 itself. This calculation has been confirmed by de Urquijo et al. [31] as noted in the experimental results.



(a) CF_3I-N_2 **(b) CF_3I-CO_2**

Figure 2.3: Density-normalized effective ionization coefficients (α-η)/N as a function of E/N at different CF_3I gas mixture ratio *k* in comparison with SF_6 [34]

2.4.1.3 Limiting field strength, E/N_{lim}

The limiting field strength, E/N_{lim} is given when ionisation is equal to attachment, $\alpha = \eta$ and when $(\alpha-\eta)/N = 0$. The critical field strength of pure CF_3I is 473 Td, and is higher than that SF_6 which is 361 Td [31], [32], [33]. Figure 2.4 depicts the E/N_{lim} values for CF_3I-N_2 and CF_3I-CO_2 mixtures in comparison with SF_6-N_2 mixture, since it has been widely used as a binary gas mixture for power equipment [34].

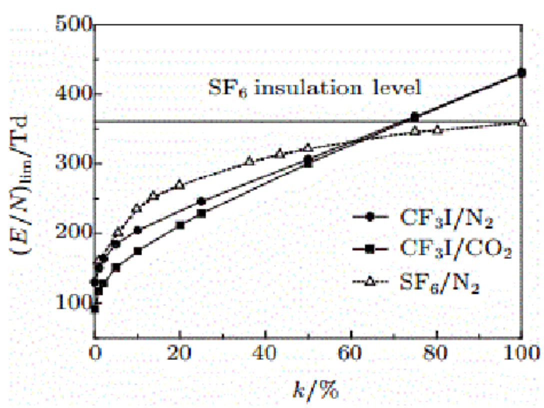


Figure 2.4: The limiting field, E/N_{lim} as a function of CF_3I and SF_6 gas content *k* [34]

For a lower content of CF_3I (< 30%) in its mixtures, E/N_{lim} of CF_3I-N_2 is higher than that of CF_3I-CO_2. In mixtures where CF_3I is more dominant, the E/N_{lim} values are the same for both mixtures, and at 60% or more of CF_3I, the E/N_{lim} values are higher than SF_6-N_2. If the content of CF_3I is more than 75%, mixtures of CF_3I with N_2 or CO_2 are even better for pure SF_6.

2.5 *Thermal Properties of CF_3I*

A good gas insulation medium for high voltage equipment should show good characteristics under high vapour pressure and high temperature. A high vapour pressure avoids the possibility of phase change from gas into liquid for a given temperature range. High thermal conductivity, on the other hand, ensures the gas has a good cooling characteristic. In this part, saturation vapour pressure curve for CF_3I is analyzed.

Duan et al. [35] measured the saturated densities of the gas from which the critical point parameters were calculated:

- critical density ρ_c 868 kg m^{-3}
- critical temperature T_c 396.44 K (123 °C)
- critical pressure P_c 3.953 MPa

In another study, Duan et al. [36] measured several vapour pressure data points for CF_3I and an analytical correlation of pressure and densities were derived. The pressure-temperature conditions of phase change are demonstrated by:

$$\ln\left(\frac{P}{P_c}\right) = \left(A_1\tau + A_2\tau^{1.25} + A_3\tau^3 + A_4\tau^7\right)\frac{T_c}{T} \qquad (2.1)$$

where

τ: $1-T/T_c$

T_c: critical temperature

P_c: critical pressure

A_i: coefficients, as shown in Table 2.4

Table 2.4: Coefficients for Eqn. (2.1) [36]

A_1	A_2	A_3	A_4
-7.19045	1.34829	-1.58035	-5.46680

The saturation vapour pressure curve for CF_3I is then plotted using MATLAB based on Eqn. (2.1). Figure 2.5 below, shows the CF_3I curve along with those for SF_6, CO_2, and N_2, which are taken from [37], [38], and [39]. Figure 2.6 shows the same curves for pressure between 0.1 MPa to 1.0 MPa.

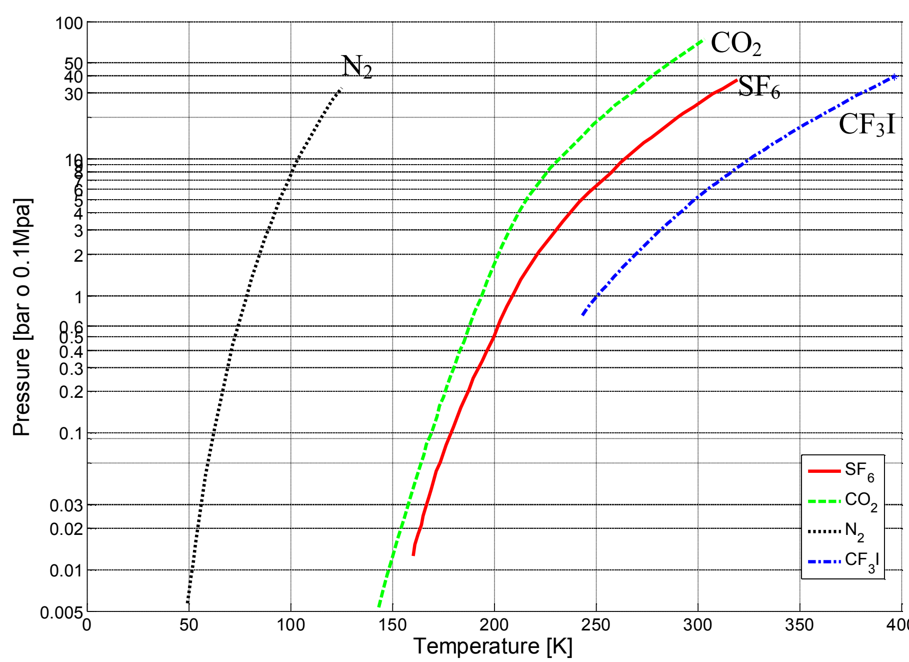


Figure 2.5: Saturation vapour pressure curves for SF_6, CO_2, N_2, and CF_3I

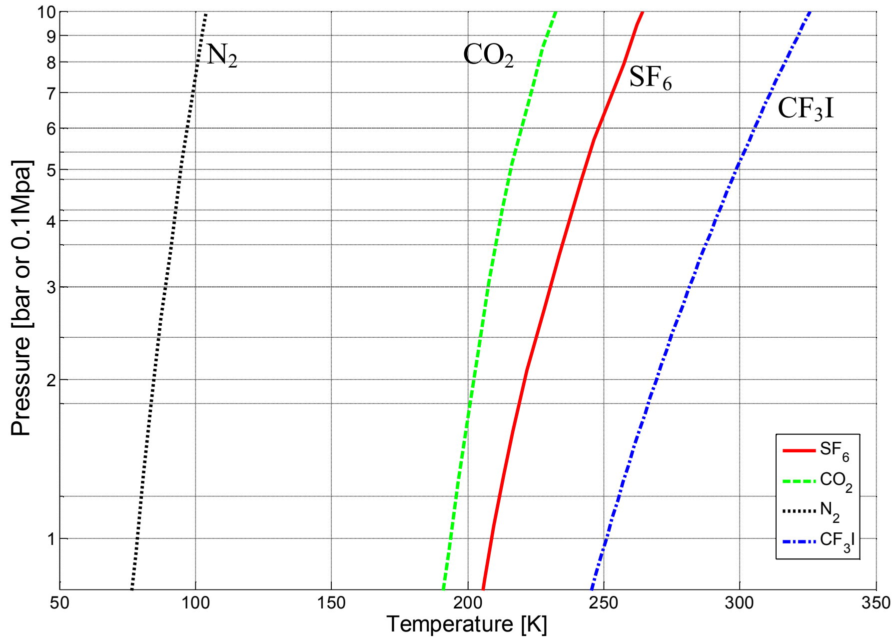


Figure 2.6: Saturation vapour pressure curves for SF_6, CO_2, N_2, and CF_3I (0.1 MPa to 1.0 MPa)

Based on Figure 2.6, at 0.1 MPa, the boiling points for CF_3I and SF_6 are approxiamately 251K (–22.15ºC) and 208K (–65.15ºC), respectively. According to Katagiri et al. [40], a typical gas-insulated circuit breaker (GCB) for GIS uses SF_6 gas at 0.5 MPa as the insulation medium. Again, by referring to Figure 2.6, at 0.5 MPa, the boiling points for CF_3I and SF_6 are given at around 298 K (24.85ºC) and 243 K (–30.15ºC). As a reference, Figure 2.7 shows the saturation vapour pressure curves for CF_3I and SF_6 as given by Katagiri in [40].

It is clear that it can be difficult to use compressed pure CF_3I in HV switchgear under these conditions. As an example, during winter times in certain countries, the temperature may drop to lower than –22.15ºC. If this occurs, then the CF_3I gas will liquefy. The adoption of other gases, such as nitrogen (N_2) or carbon dioxide (CO_2) as a mixture in CF_3I, helps in reducing the boiling point, and it is absolutely required for outdoor application. This is required in order to prevent CF_3I from liquefying.

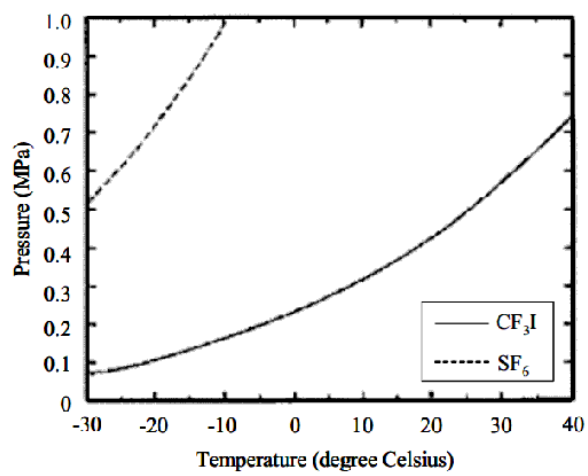


Figure 2.7: Saturation vapour pressure curves for CF_3I and SF_6 as given by [40]

According to Dalton's law, the total pressure of mixture of gases equals the sum of the pressures that each would exert if it were present alone as depicted in Eqn. (2.2) below.

$$P_T = P_1 + P_2 + \ldots + P_n \qquad \text{or} \qquad P_T = \sum_{i=1}^{n} P_i \qquad (2.2)$$

where

$P_1, P_2, \ldots, P_n$ represent the partial pressure of each gas

Kasuya et al. [41], [42] and Katagiri et al. [40], [43] reported that at 0.5 MPa, the boiling point of CF_3I-CO_2 (40%-60%) and CF_3I-CO_2 (30%-70%) gas mixtures are about –5 ºC and –12 ºC, respectively. Referring to Figure 2.6, the boiling point for pure CF_3I gas at 0.5 MPa is around 300 K (26.85 ºC). Further discussion on the boiling point of CF_3I-CO_2 gas mixtures is presented in Section 6.3.3.

2.6 *Electrical Properties of CF_3I and Its Mixtures*

Insulation properties, such as voltage-time (*V-t*) characteristics, 50% breakdown voltage (U_{50}), and interruption capabilities, need to be investigated before a gas or gas mixture is used as a gas insulation medium in high voltage applications. Many researchers are focusing on mixing CF_3I with either CO_2 or N_2, since both gases are easily available and have a much lower boiling point [40], [44], [41]. However, due to the fact that CF_3I has just recently become known (less than 20 years) to have promising insulation characteristics, investigation reports on CF_3I and its mixtures are not as many as for SF_6. Only recently has there been progressive work on CF_3I mixtures. Hence the opportunity to explore its capabilities as an insulation medium is expansive.

2.6.1 50% Breakdown Voltage (U_{50})

It is possible to investigate U_{50} as a self-restoring insulation, such as a gas insulator, and in this case, CF_3I. U_{50} can be evaluated by using two methods [45]:

i. the multiple-level method with at least four (4) voltage levels, and at least ten (10) impulses per level, and

ii. the up-and-down method with one (1) impulse per group and at least twenty (20) useful applications.

2.6.1.1 50% Breakdown Voltage (U_{50}) of CF_3I

It is known that CF_3I has a dielectric strength of around 1.21 times higher than SF_6 [23], [30]. Toyota et al. [46] evaluated U_{50} for both SF_6 and CF_3I gases in their research. Under the application of a steep front square voltage with a wave front of 16 ns, Toyota measured the U_{50} using the up-and-down method, and the results are shown in Table 2.5. The measurements were carried out with a rod-plane gap, with the tip radius of the electrode is given as 0.4 mm, the pressure was 0.1 MPa.

Table 2.5: 50% breakdown voltage, U_{50}, for SF_6 and CF_3I gases at 0.1 MPa under steep front square voltage application [46]

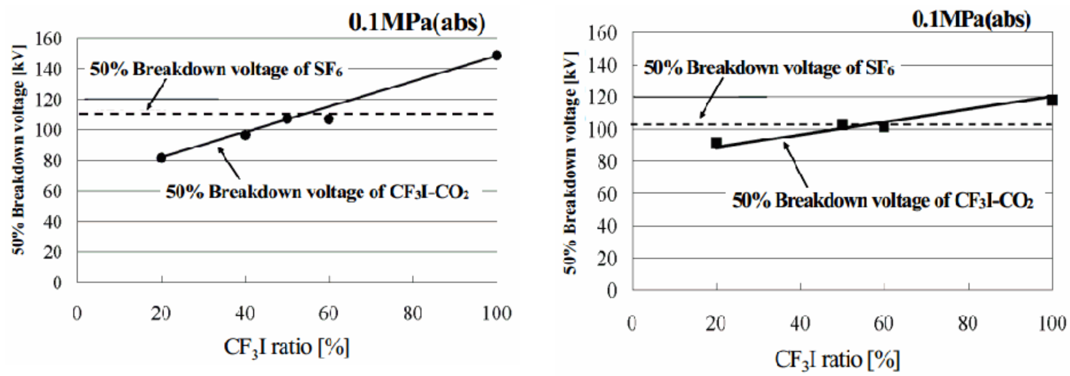
Gas	Gap length	Polarity	U_{50}
SF_6	10 mm	Positive	47 kV
		Negative	–52 kV
	20 mm	Positive	64 kV
		Negative	–98 kV
CF_3I	10 mm	Positive	35 kV
		Negative	–61 kV
	20 mm	Positive	46 kV
		Negative	–84 kV

From the above table, for a gap length of 10 mm, U_{50} for CF_3I is around 0.74 times lower than SF_6 under positive polarity, but 1.17 times higher than SF_6 under negative polarity. Meanwhile, for a gap length of 20 mm, in both polarities, U_{50} for CF_3I is lower than SF_6, with 0.72 times under positive polarity and 0.86 times under negative polarity.

However, there is inconsistency within the negative polarity results. For a 10 mm gap length, U_{50} for CF_3I is lower than SF_6, while it is higher in a 20 mm gap length. This is due to a change in the gap geometry, and hence, a change in field utilization factor. For a rod-plane electrode system, an increase in gap length will result in a decrease in field utilization factor, which represents more non-uniform electric field configuration. As have been reported by Takeda et al. [47], CF_3I has lower sparkover voltages in lower field utilization factors, as compared to SF_6.

2.6.1.2 50% Breakdown Voltage (U_{50}) of CF_3I Mixtures

Further tests on U_{50} have been carried out by Katagiri et al. [40]. For these measurements, CF_3I was mixed with CO_2 in various ratios to investigate the effects of CF_3I content on a given test condition. By applying standard lightning impulse voltage, with a sphere gap of 10 mm apart, the results on the aforementioned tests were obtained (see Figure 2.8).



(a) Positive polarity **(b) Negative polarity**

Figure 2.8: U_{50} for CF_3I-CO_2 mixtures [40]

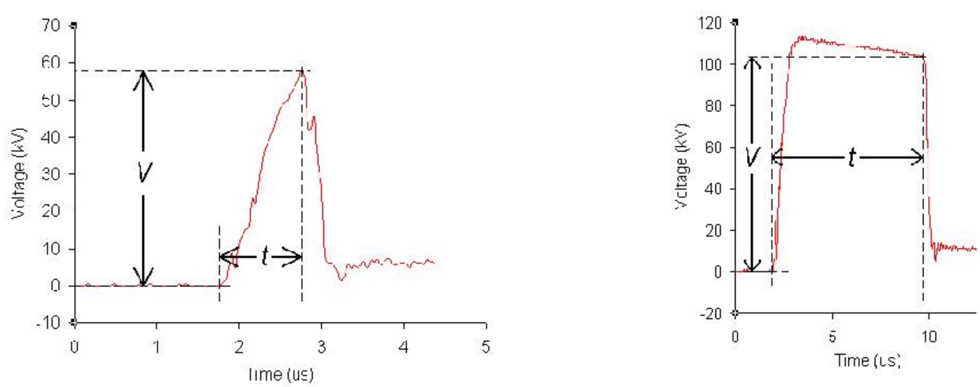
For this electrode system, it is clear that the U_{50} for pure CF_3I is higher than the given U_{50} of SF_6, which is around 1.2 times better. In both polarities, the U_{50} curves increase linearly with the proportion of CF_3I. At a CF_3I ratio of 60%, the dielectric strength of the CF_3I-CO_2 mixture is close to that of SF_6. The U_{50} for SF_6 presented is higher than the rated 89 kV, due to the tests being carried out with lightning impulse, where statistical effect of electron production plays a major role. According to Anis and Srivastava [48], the space charge due to corona under lightning impulses does not have sufficient time to stabilize, which is also related to rate of production of initiatory electrons. A lightning impulse, which happens in a very short period, then requires higher electric field (and hence higher voltage) to provide a condition for breakdown.

Under static electric field conditions, such as in dc voltage, the U_{50} for SF_6 would be around 89 kV.

However, according to Katagiri et al., because of the high boiling point of CF_3I, the proportion of CF_3I in the mixture should not be more than 30% which gives the dielectric strength of CF_3I-CO_2 (30%-70%) of around 0.75 to 0.8 times that of SF_6. It should be noted that these measurements were carried out with only fifteen (15) breakdown tests [40]. If the measurements were using an up-and-down method, the tests should be carried out with at least twenty (20) useful applications to conform to the international standard BS EN 60060-1 (2010) [32].

2.6.2 *V-t* characteristics

Another characteristic used to evaluate the insulation performance for a gas, considers the *V-t* characteristic which represents the relationship between the breakdown voltage and time to breakdown. If the voltage used in the measurements 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, as shown in Figure 2.9.



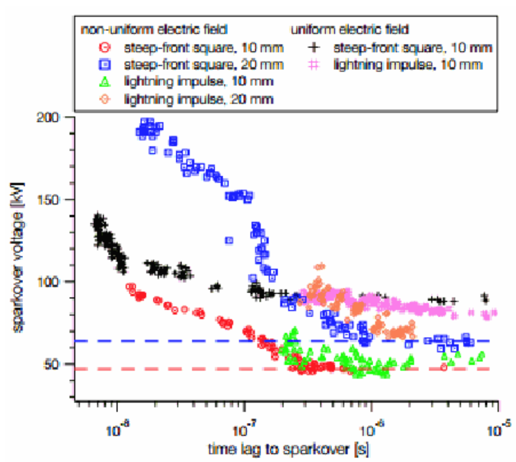
(a) (b)

Figure 2.9: Breakdown (a) before and (b) after peak of lightning impulse

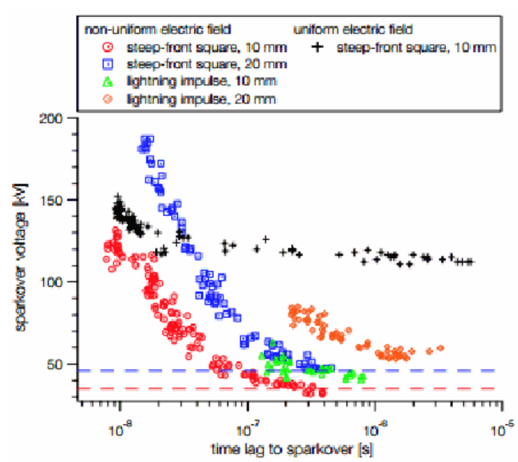
2.6.2.1 *V-t* characteristics of pure CF_3I

In 2005, Toyota et al. [46], [49] compared CF_3I *V-t* characteristics with SF_6, with emphasis given to non-uniform field conditions. Toyota applied a steep-front square voltage with a front wave of 16 ns and a peak value up to 200 kV. These short time range measurements are useful in dealing with very fast, transient overvoltage problems caused in GIS. Another impulse voltage has been used in the tests characterised as 1.8/450 µs, in which the wave front was similar to the lightning impulse.

The electrodes were configured as rod-plane system, with a radiation source installed behind the plane electrode to promote the initial electrons generation. By using Cobalt-60, the electrons are accelerated towards the anode. This irradiation technique was used to overcome the statistical variability [48]. The results are shown in Figure 2.10 and Figure 2.11.

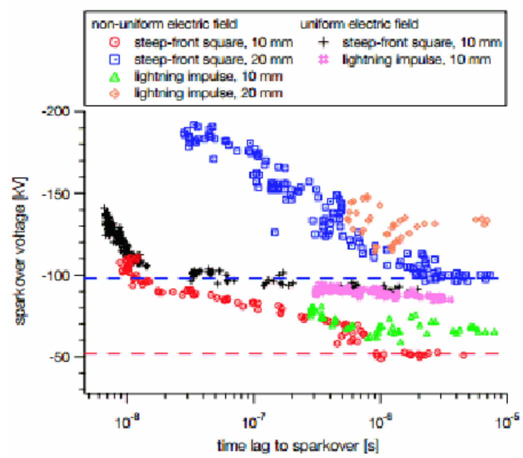


(a) SF_6

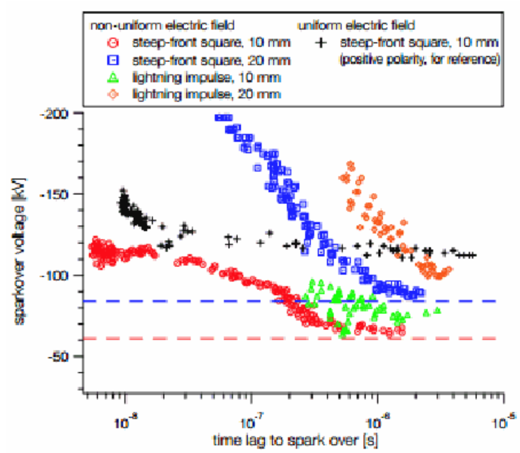


(b) CF_3I

Figure 2.10: *V-t* characteristics at 0.1 MPa [46] **under positive polarity. Dashed lines indicate U_{50} in Table 2.5**



(a) SF_6



(b) CF_3I

Figure 2.11: *V-t* characteristics at 0.1 MPa [46] **under negative polarity. Dashed lines indicate U_{50} in Table 2.5**

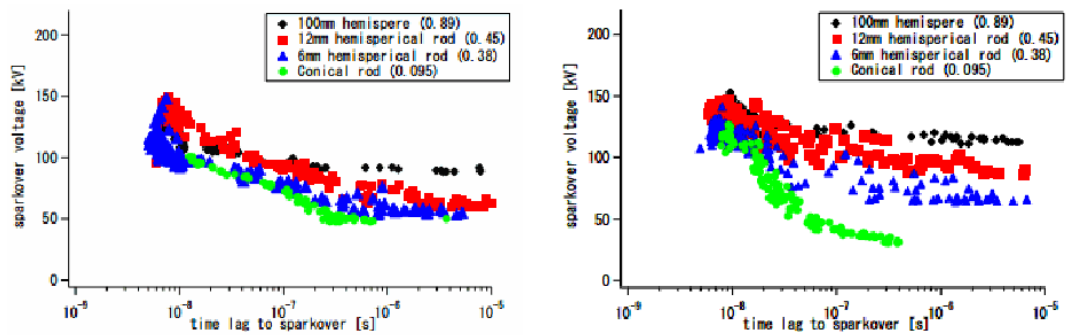
Toyota found that for the same period, in the time lag (t), the sparkover voltage (V) under steep front square voltage is lower than those at 1.8/450 µs lightning impulses (non-standard). This effect is not easily explained.

Takeda et al. [47], [50], [51] carried out further tests on *V-t* characteristics for CF_3I with more options in electrode configurations, by applying the same steep front square voltage. The field utilization factor, which is a function of the geometrical characteristic (the mean electric field/the maximum electric field) for each electrode configuration are shown in Table 2.6. Takeda's findings are summarized in the Figure 2.12.

Figure 2.12 shows that higher field utilization factors (0.38 onwards) for CF_3I, have higher *V-t* characteristics (the *V-t* characteristics shifted upwards), while for a low field utilization factor, SF_6 is better in terms of *V-t* characteristics. This might be of interest since in order for CF_3I to replace SF_6 fully as an insulation medium, CF_3I has to have a better *V-t* characteristics for all types of electrode configurations, since they represent various kinds of high voltage apparatus.

Table 2.6: Field utilization factors for different electrode configurations [47]

Electrode configuration	Field utilization factors
100 mm hemisphere	0.89
ϕ 12 mm hemispherical rod	0.45
ϕ 6 mm hemispherical rod	0.38
Conical rod (r=0.4 mm)	0.095



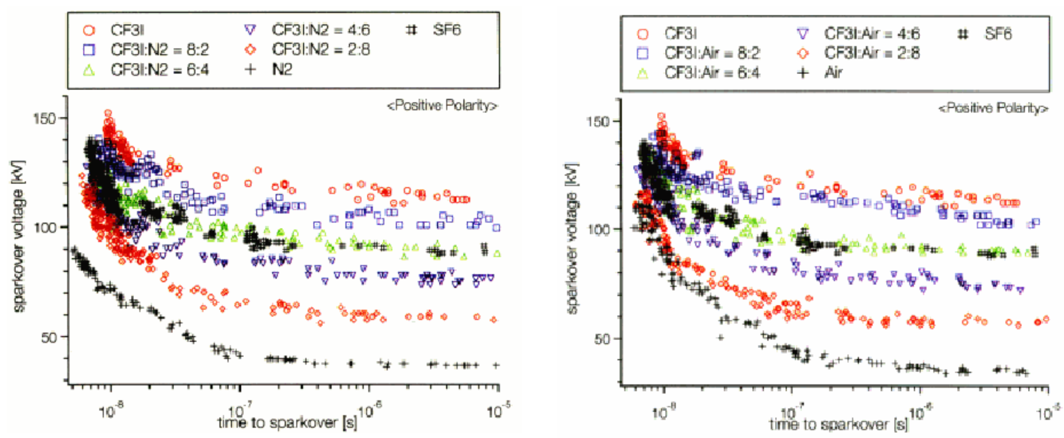
(a) SF_6 **(b) CF_3I**

Figure 2.12: *V-t* characteristics for gap 10mm; positive polarity [47]

2.6.2.2 *V-t* Characteristics of CF_3I Mixtures

In 2006, Nakauchi et al. [52] reported that sparkover voltage in a CF_3I-N_2 mixture is almost the same as that in a CF_3I-CO_2 mixture under square pulse voltage. Toyota et al. [49] carried out further tests on *V-t* characteristics for several CF_3I mixtures, namely CF_3I-N_2 and CF_3I-Air mixtures. A 50 mm radius hemisphere-to-plane electrode is used in the tests, giving a field utilization factor of 0.89 when the gap is 10 mm. Again, the CF_3I mixtures were subjected to steep front square wave voltage with a rise time of 20 ns. The total pressure of the gas is 0.1 MPa. The tests are carried out for positive polarity only. Figure 2.13 shows the summary of these findings [49].

It can be concluded that the *V-t* characteristics for both CF_3I-N_2 mixtures are almost identical. For both mixtures, with a CF_3I ratio at 60%, the *V-t* characteristics will be the same as that of pure SF_6, as has also been reported in [53]. Therefore, the same dielectric strength is obtained. This is the same amount Katagiri et al. [40] reported in the investigation on U_{50} for CF_3I-CO_2 mixtures, in which around 60% of CF_3I, the CF_3I-CO_2 mixture gives approximately the same voltage level as U_{50} for SF_6.



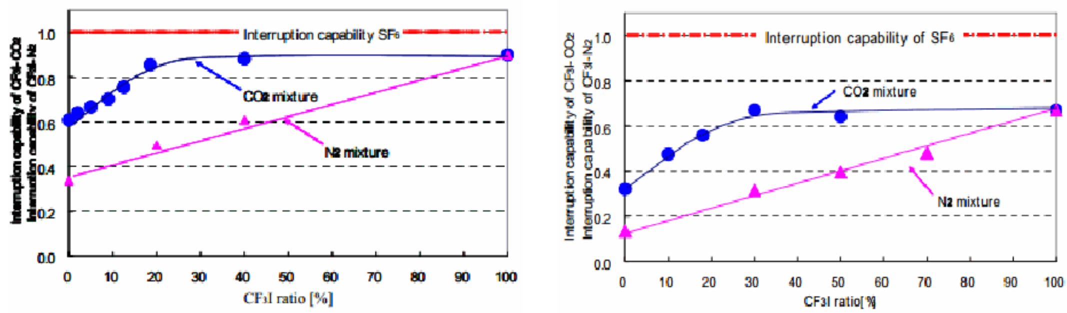
(a) CF_3I-N_2 **(b) CF_3I-Air**

Figure 2.13: *V-t* characteristics at 0.1 MPa [49]

2.6.3 Other electrical properties for CF_3I and its mixtures

Interruption capabilities of CF_3I have been investigated by Katagiri et al. [40] and [54], Taki et al. [44] and Kasuya et al. [41]. Using a model of an arc-extinguishing chamber, the authors investigated short line fault (SLF) and breaker terminal fault (BTF) interruption capabilities of CF_3I, CF_3I-N_2, and CF_3I-CO_2 mixtures compared to SF_6. It was found that although dielectric strength of CF_3I is 1.2 times higher than SF_6, SLF interruption performance of CF_3I is around 0.9 times that of SF_6, and BTF interruption performance is almost 0.7 times that of SF_6.

Katagiri also reported that the interruption performance of CF_3I-CO_2 mixtures is higher than CF_3I-N_2 mixtures. This is thought to be due to the electron attaching properties of CO_2 which are better than N_2. A clearer view of this is depicted in Figure 2.14. An interesting point to be considered is that for CF_3I-CO_2 mixtures with at least 30% of CF_3I, interruption performance is almost the same of that of pure CF_3I. This gives a good indication, in terms of boiling point, of the gas mixture.



(a) SLF **(b) BTF**

Figure 2.14: Interruption capabilities of CF_3I, CF_3I-N_2 and CF_3-CO_2 mixtures as compared to SF_6 [40]

Takeda et al. [47] and [55] carried out further tests on CF_3I to investigate surface flashover characteristics. A polytetrafluoroethylene (PTFE) dielectric is placed between two plane electrodes, immersed in CF_3I gas, with the application of steep front square wave voltage. It was found that, upon a surface discharge in CF_3I, the subsequent flashovers are lower than the previous ones. Upon investigation, a brownish material is found to be deposited on the PTFE surface, and this was later identified as iodine. The deposition of iodine increases with each flashover. It is possible that solid iodine deposited along the path of flashover may conduct current and, hence, may decrease the insulation performance of CF_3I gap.

2.7 By-products of CF_3I

One of the major concerns in SF_6 use is by-product production upon electrical discharges. SF_6 by-products, such as SO_2F_2, SiF_4, and SO_2, are very irritating to the eyes, nose, and throat [19]. Due to this, the need to investigate the by-products of CF_3I, particularly in terms of insulation performance and dielectric strength are present.

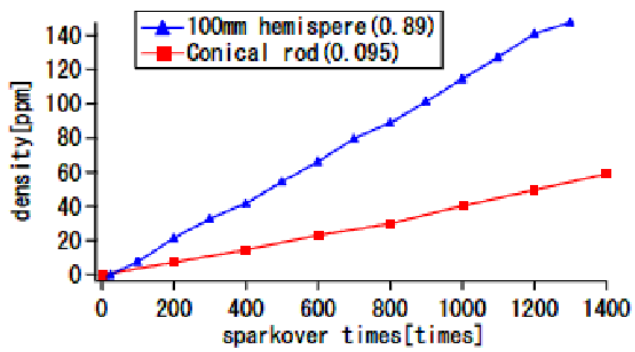


Figure 2.15: Relation between C_2F_6 and amount of sparkover times with different electrodes [57]

Investigations on gaseous decomposition of CF_3I have been carried out by Takeda et al. [47] and [57] and Kamarol et al. [58], using gas chromatography-mass spectrometry (GC-MS) to measure the by-products qualitatively and quantitatively. In the measurements, C_2F_6, C_2F_4, CHF_3, C_3F_6, C_3F_8, and C_2F_5I are detected as gaseous by-products generated by sparkover. In these investigations, the amount of these by-products is found to be higher under uniform fields than that in non-uniform fields. This is due to the fact that higher breakdown voltage is needed in uniform fields, which related proportionally to the energy (energy, $E \propto V^2$) produced during the breakdown. C_2F_6 has the highest quantity among the gases, and this decomposition seems to be linearly increased in conjunction with amount of sparkover time, as depicted in Figure

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