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REVIEW

Potential of Eco-Friendly Gases to Substitute SF_6 for Electrical HV Applications as Insulating Medium: A Review

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ABSTRACT

Compressed gas is an essential ingredient for high-voltage (HV) applications, especially as an insulating medium. Sulfur hexafluoride (SF_6) gas due to its excellent insulating features is being preferred for decades and is widely utilized in applications such as gas-insulated switchgear, gas-insulated bus bars, circuit-breakers (CB), etc. But its global warming potential has been reported at the utmost harmful level. Many environmental anomalies have been produced by greenhouse gases, the reason why this problem has got extraordinary consideration, and there is an emergent need to introduce some eco-friendly substitute for SF_6. The research was started almost 4 decades ago to find a replacement for SF_6; however, progress in recent years is much better than earlier. Now, many alternatives have been searched out, and tests are being performed to find the best of them. In this study, the progress of some eco-friendly gases such as natural gases, trifluoroiodomethane, dichlorodifluoromethane, tetrafluoroethane, perfluoroketones, and heptafluoroisobutyronitrile has been summarized, keeping in view the basic physical properties and electrical insulating features. Decomposed by-products and boiling point were also discussed in detail, and the conclusion deduced that perfluoroketone and heptafluoroisobutyronitrile, with mixture of natural gases, show much better potential to replace SF_6 in many of the HV applications; later one has a bit upper edge.

Index Terms—Boiling point, circuit breakers, decomposed by-products, dielectric strength, gas-insulated switchgear, global warming potential

I. INTRODUCTION

There is a certain reason for increased usage of sulfur hexafluoride (SF_6) for years because of some limitations of air and oil such as more space required for the technical development of higher voltage range [1]. Air is a mixture of low electronegative gases and so its breakdown strength is very low, and to obtain a higher voltage range, it requires a lot of space. The maintenance of oil is poor, and also, it is a fire hazard. So, SF_6 gas is being considered as the best insulating medium because it requires less maintenance and is very safe to operate [2].

The main feature of SF_6 is its dielectric breakdown strength that is almost three times more than that of air, which is a strong electronegative gas. Space between electrodes is decreased due to its higher breakdown strength, resulting in smaller equipment [1, 2]. Another feature of SF_6 is its arc-quenching capability with excellent dielectric recovery strength, as its molecules reform very quickly after an arc or electrical discharge [3]. It also exhibits good heat transfer and thermal interrupting properties. Some other important properties of SF_6 were as follows: it is a non-toxic [4], non-flammable, colorless, and odorless gas and is chemically and thermally very stable.

But, the two significant issues related to SF_6 utilization in electrical equipment are its very high global warming potential and its bit higher liquefaction temperature.

First, global warming potential of SF_6 is more than 23 000, which can sustain over 100 years, and Kyoto Protocol identified SF_6 as one of the six major greenhouse gases [5, 6], in which the harmful level indicates that SF_6 badly affects the environment. SF_6 was labeled as regulated gas at third Framework Convention on Climate Change [7],

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apart from this, Paris (France) Agreement 2016 also demands zero emission of greenhouse gases in later half of the century [8]. Its liquefaction temperature is also bit higher, relative to some natural gases, which is −64°C at 0.1 MPa [9]. SF_6 also has some other adverse properties like corrosion and toxic by-products formation resulting from electrical discharges. At the time, China is the leading country in emission of SF_6, and 70% of it comes from electrical equipment, followed by semiconductor manufacturing, magnesium production, and SF_6 preparation, each contributing around 10% of the remaining [10]. The leakage rate of SF_6 is very low, but debugging, recycling of SF_6, normal leakage and maintenance of SF_6-insulated switchgears, circuit-breaker (CB), etc. contribute to emission in atmosphere. More advanced detectors for leakage should be adopted to reduce SF_6 gas emission [11], and campaign should also be initiated to endorse recycling processes. But still, this will not be enough to eliminate greenhouse effect and toxic decomposed by-products. SF_6 gas has been utilized up to the range of 800 kV because there were no alternatives available with the same insulation and quenching properties, the main features of insulating medium. But now, there are many alternatives that show much potential for replacement. Some review articles have also been published in recent years in which some useful comparison between available options has been made. For example, an overview of green gas for the application of switchgear, in comparison with SF_6, was published [12]; however, the article did not consider other potential options. Similarly, some other articles [13, 14] have also reviewed the potential replacement but either covered very few options or missed some properties to discuss. So, in this article, efforts have been made to include every potential option of replacement with discussion on most concerned features.

II. ECO-FRIENDLY SUBSTITUE GASES

Eco-friendly substitute gases of SF_6 must have safety and environmental needs that should be fulfilled, that is, they should be non-toxic and non-flammable, but the two major features of being eco-friendly which cannot be compromised are low global warming potential (GWP) and zero ozone depletion potential.

In addition, some other features needed for usage in electrical HV equipment are:

i. excellent dielectric strength (high withstand and breakdown voltage level);
ii. excellent arc-quenching capability with fast dielectric recovery;
iii. low boiling point with a high cooling capacity;
iv. high heat dissipation;
v. should be chemically and thermally stable;
vi. compatible with the material of circuit breaker, transmission line, switchgear, and design compactness.

Among natural gases, nitrogen (N_2) and carbon dioxide (CO_2) being easily available, non-toxic, non-combustive, and with stable physicochemical properties made them the first choice of consideration as alternatives for SF_6, almost 4 decades ago. N_2, one of the most stable and inert gas, exhibits zero GWP [15], while GWP of CO_2 is taken as one, which makes both of them eco-friendly.

Another compound named trifluoroiodomethane having formula CF_3I is under consideration. It is an odorless and colorless gas with GWP only around 0.5 and lifetime around 2 days. Its ozone depletion potential is almost zero, which is another encouraging feature. CF_3I has some other useful potentials such as being used in semiconductor etching and foaming agents, etc. National Fire Protection Association authenticated CF_3I as a fire extinguishing agent [16] and as an optimal alternative for Halon.

($C_nF_{2n}O$) is the generic formula for fluoroketones which have been used as fire extinguishers for the last one decade and so. C_6F-ketone has dielectric strength around 1.7 times of SF_6 showing an excellent insulating capability [17]. Its toxicity level is also low, and more importantly, it has GWP level of around 1 with an atmospheric lifetime of only a week. C_4-PFK and C_5-PFK are other compounds from the same family with lower molecular weight and lower boiling point, and they exhibit almost equivalent dielectric strength as C_6F-ketone [18].

Dichlorodifluoromethane (R_{12}) and tetrafluoroethane (R_{134}) have recently been introduced as alternatives to SF_6, exhibiting relevant features, such as lower GWP with less atmospheric lifetime and good self-recoverability [16, 19, 20].

Heptafluoroisobutyronitrile is a compound from fluoronitrile family with formula (C_4F_7N), which is commercially accessible with the name 3M™ Novec™ 4710 dielectric fluid. The fluid got attention because its GWP is almost 10 times lower than that of SF_6, which is around 2100, with dielectric strength almost twice that of SF_6 at atmospheric pressure [17]. It also has high thermal transfer capability, and its toxicity level is quite low.

A. Basic Physical Properties

Basic physical properties are important in a sense because these determine the arc-quenching capability and dielectric strength. Relations are very complex, but still, properties are helpful to assess the potential of insulating medium. Studies of basic physical properties with comparison have been carried out that primarily include thermal and electrical conductivities. Temperature dependence of electrical conductivity is almost similar for most of the alternative gases [21], as shown in Fig. 1.

The electrical conductivity of most gases start increasing from 7000 K, but SF_6 and CF_3I start a bit earlier around 5000 K. It is due to the presence of sulfur and iodine, respectively, which have lower ionization energies. Increase is almost steady till 24 000 K. Unlike electrical conductivity, thermal conductivity behavior is much different and depends strongly on the nature of the gas. Typical characteristics are shown in Fig. 2, which clearly reveal that there are some peaks at lower temperature and some at higher temperature [22, 23].

Peaks at a lower temperature are associated with dissociation, and higher temperature peaks are due to ionization. SF_6, CF_3I, and their mixture exhibit many dissociation peaks due to successive dissociation reactions. As far as ionization peak is concerned, SF_6 and its mixture have peaked around 17 000 K almost 2000 K higher than other gases. This is due to the presence of fluorine that has higher ionization energy. In recent years, mixtures such as SF_6/Cu [20], CO_2/Cu

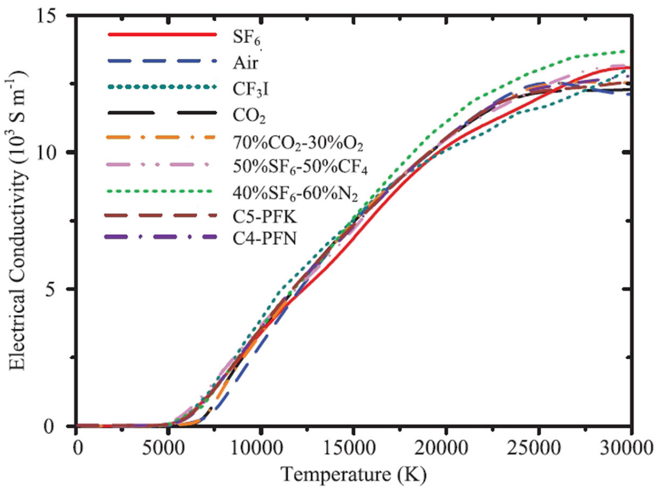

Fig. 1. Electrical conductivity of gases vs. temperature [21].

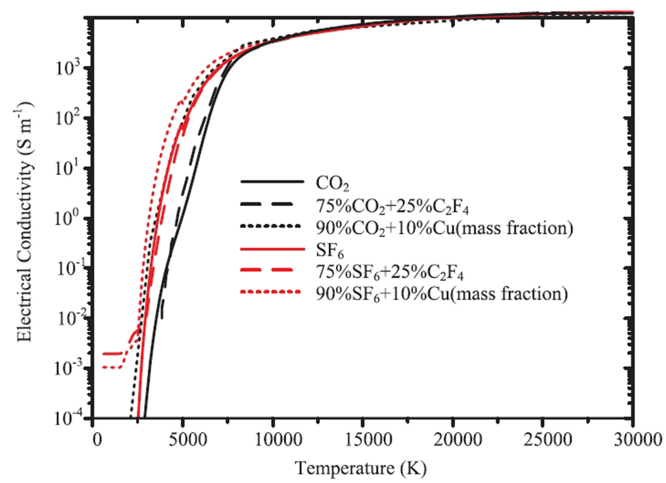

Fig. 3. Thermophysical properties of mixture (electrical conductivity) [26].

[24, 25], and air-CO_2-SF_6/polytetrafluoroethylene (PTFE) have been studied for thermophysical properties [26, 27]. Some of the results are shown in Fig. 3 and 4.

It is obvious from the figures that low ionization energy of metal improves electrical conductivity and makes it to start at lower temperature and rises with higher slope. But, there was no significant change in thermal conductivity; however, PTFE addition increases thermal conductivity and also helps to increase pressure in arc-quenching chamber as well, which boosts the thermal cooling capability of the medium. It was also concluded that the addition of PTFE in CO_2 has more effect as compared to addition of SF_6 for thermal conductivity and that the addition of Cu in CO_2 has a significant change in electrical conductivity at lower temperature regions as compared to SF_6.

Ionization potential of gas is another important factor to understand collision behavior during the breakdown process. Table I gives the comparison of ionization potential of gases, which reveals SF_6 has the highest ionization potential. SF_6 can easily attach to low-energy electrons and hence reduces free electron density owing to good dielectric strength. CF_4, C_3F_8, C_2F_6, and CO_2 also have some reasonable ionization potential.

B. Dielectric Strength

At early stage, when research was started to find the replacement for SF_6, natural gases or mixed gases were experimented, and it was found that the dielectric strength of mixed gases with SF_6 is slightly better than that of pure gases [28-30]. Generally, electronegative gases exhibit good dielectric strength but have high boiling point. In contrast, non-electronegatie gases such as CO_2 and N_2 have low boiling point and low dielectric strength, some fraction of SF_6 (i.e. around 0.4–0.45) [15]. To use natural gases, more volume or high pressure is required to meet the dielectric strength which leads to a significant increase in size and cost, which is undesirable

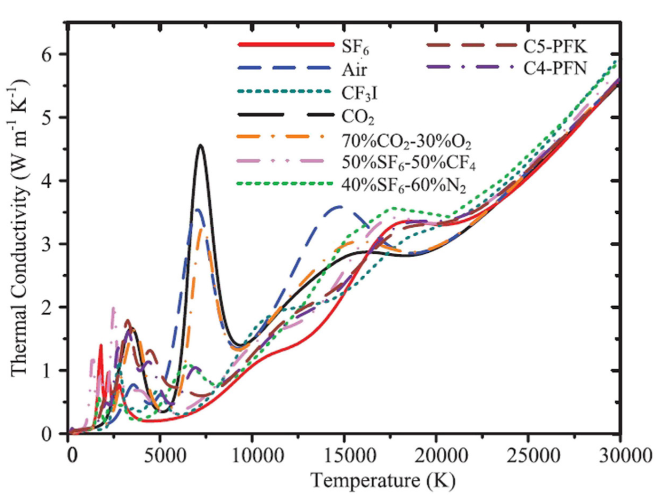

Fig. 2. Thermal conductivity of gases vs. temperature [22].

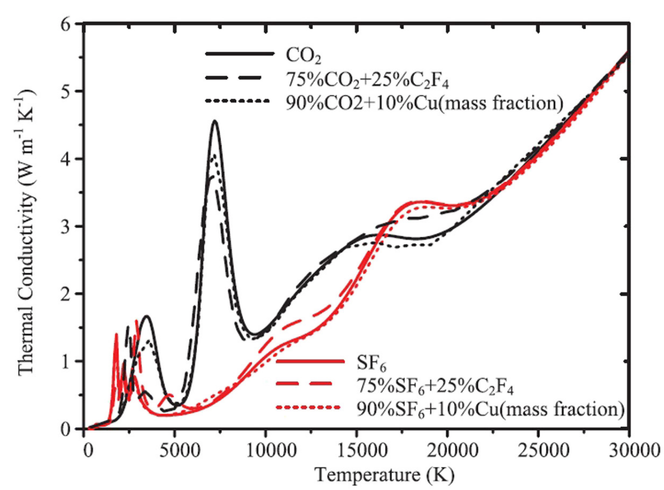

Fig. 4. Thermophysical properties of mixture (thermal conductivity) [26].

for design consideration. Table I summarizes the comparison among pure natural gases and some other substitutes under consideration vs. SF_6. Dry air was also tested in the last 2 decades and successfully used for medium voltages such as 12 kV/24 kV; ring network cabinet uses dry air or N_2 [30, 31], but its dielectric strength is also too low that it requires high pressure. Pure CF_3I has higher dielectric strength as compared to SF_6, almost 1.2 times of SF_6 in comparison with other gases that are depicted in Table I.

CF_3I/N_2 or CF_3I/air mixtures having 60% of CF_3I exhibit almost the same *v*–*t* characteristics as that of SF_6 under same pressure [32]. Breakdown test was conducted for the mixture (CF_3I/CO_2) with a ratio of 30%/70% which exhibits dielectric strength almost 0.8 times of that of SF_6 [33, 34].

Recently, studies have been conducted for the mixture of CF_3I/N_2 [35, 36]. In non-uniform AC field configuration with plate–needle, the result showed that the CF_3I/N_2 mixture with a ratio of 30%/70% has dielectric strength 0.9 times of that of SF_6 up to distance of 5 mm at 0.3 MPa, which is even better than pure CF_3I in non-uniform field, exhibiting positive synergistic effect [33]. Lightning impulse test was carried out to investigate the withstand voltage performance under lightening impulse for 252 kV gas-insulated transmission lines [33], and it was found that CF_3I/N_2 mixture with ratio of 20%/80% exhibits withstand performance 0.9 times of that of SF_6/N2 of same ratio and 77% of pure SF_6 pure.

Gas-insulated switchgear (GIS) 145 kV was tested for withstand voltage with air and C_6F-ketone, and the result was almost the same as the dielectric strength of SF_6. For this, GIS has filling pressure of 6 bar, while C_6F-ketone has 0.6 bar with temperature of 35°C below which C_6F-ketone will liquefy [17].

Mixture R_{12} with N_2 in ratio of 80%/20% shows almost 90% higher dielectric strength than that of SF_6 gas at 50 lb/in^2 under AC voltage, while R_{134} with N_2 in 80%/20% ratio shows 85% higher strength than that of SF_6 [19, 20]. It was also found that further addition of R_{134} and R_{12} does not bring a rapid increase in breakdown voltage due to low energy electron attachment [19, 20]. Synergistic effect was found positive for more than 70% content of dichlorodifluoromethane with pressure at least 25 lb/in^2 [19].

Dielectric strength of heptafloroisobutyronitrile (C_4F_7N) is almost twice of SF_6 at atmospheric pressure [17, 37], as shown in Table I, but its liquefaction temperature being high enforced researcher to use it with mixture. Literature shows that CO_2 was found to be the best one to mix [17, 37-42]. Mixture of (C_4F_7N) with CO_2 is termed as green gas (g^3). Depending on minimum operating temperature and maximum filling pressure, g^3 and (C_4F_7N) mixing ratio may vary, like 4%, 6%, 10%, or 20% of volume. It was found that GWP of the (C_4F_7N/CO_2) mixture in 4%/96% ratio was only 378, around 1.6% of SF_6 [38]. The power frequency dielectric strength of (C_4F_7N/CO_2) mixture with mixing ratio of 18%/20% volume of (C_4F_7N) content is almost equivalent to SF_6 [37, 40]. Fig. 5 explains dielectric strength variation with varying mixing ratio. Lightening impulse test shows that dielectric characteristics at 0.88 MPa and 1.04 MPa are similar to SF_6 at 0.55 MPa and 0.65 MPa [37, 40], respectively. In a uniform field with plane–plane electrode configuration, dielectric strength for (C_4F_7N/CO_2) with a mixing ratio of 15%/85% was found to be 85.29 kV/mm under 0.1 MPa pressure, which is very near to SF_6, with 86.30 kV/mm for identical pressure [42]. And when contents of (C_4F_7N) were increased to 20%, the mixture exhibited a dieclectric strength of 90.25 kV/mm higher than SF_6 [42]. So, (C_4F_7N) with CO_2 is a very promising substitute to replace SF_6 in terms of dielectric strength.

TABLE I.
GWP AND DS OF VARIOUS SUBSTITUTES IN COMPARISON WITH SF_6. [9,15,18,42-40,48,62,73,74-77]

Gas Formula	GWP	Dielectric Strength (p.u)	Ionization Potential (eV)	Boiling Point (°C at 0.1 MPa)
SF_6	~23 000	1	15.32	−63
Air	0	0.43–0.5	–	−194
CO_2	1	0.45	13.78	−79
N_2	0	0.4		−196
CF_3I	~0.5	1.21	10.28	−22.5
C_6-PFK	1	>2	–	49
C_5-PFK	1	~2	11.03	27
C_3F_8	8800	0.9	13.38	−37
C_2F_6	12 200	0.76	13.6	−78.1
R_{12}	2400	0.9	–	−29.8
R_{34}	1300	0.85	–	−27
C_4F_7N	~2100	2.2	11.88	−4.7

C. Arc Quenching

Dry air and CO_2 have shown auspicious characteristics as far as arc-quenching mechanism is considered. It has been experimented that

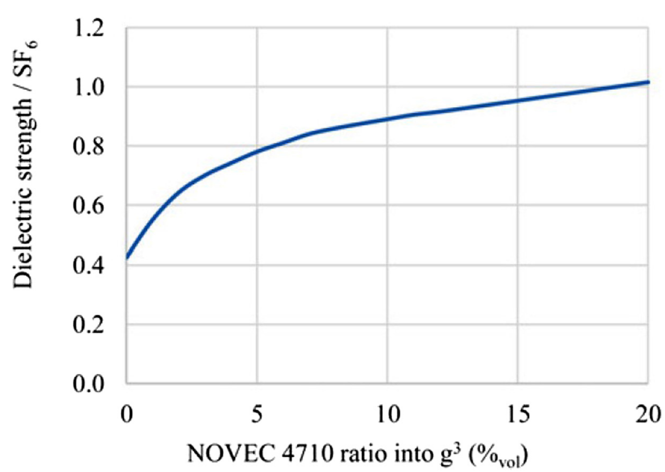

Fig. 5. Comparison of dielectric strength of SF_6 vs. C_4F_7N/CO_2 with different mixing ratio [41].

an increase in pressure from 0.2 MPa to 0.6 MPa increases power loss from 0.32 kW to 0.78 kW for CO_2 as arc-quenching medium, and time constant decreases from 1.3 µs to 0.7 µs with a max value of 1.1 kA [43]. Thermal interruptions of CO_2, SF_6 and some other gases have also been experimented [44-47], to find a comparison of post arc capabilities. Some of the results are depicted in Table II, and characteristic curves have been represented in Fig. 6.

As far as the mixture of gases is concerned, SF_6/N_2 has attracted much attention due to its synergistic effect in dielectric strength and arc interruption. It was also found that a better rate of rise of recovery voltage (RRRV) can be obtained if appropriate ratio of N_2 is mixed with SF_6 [48]. Mixture containing 31% of N_2 and 69% SF_6 exhibited much improved RRRV as compared to SF_6 only [49]. Puffer type gas circuit breaker was experimented with mixture of 0.2 MPa-N_2/0.3 MPa-SF_6 and got 0.76 times more d*i*/d*t* than that of pure SF_6 [49]. Critical RRRV and d*i*/d*t* were very much improved by increasing SF_6 contents in the mixture of SF_6/CO_2 [50]. For 126 kV puffer type gas circuit breaker, if SF_6 concentration is increased from 0%, 20%, and 50%, then RRRV before current zero improves from 39%, 45%, and 70%, respectively [51].

The arc extinguishing capability of pure CF_3I is around 90% of that of SF_6 but pure CF_3I has a bit higher boiling point as compared to SF_6 and cannot be used in extremely cold regions [52]. Again, the mixture with natural gases showed improved boiling point as well as arc extinguishing capability [52]. For mixtures of (CF_3I/N_2), (CF_3I/CO_2), and CF_3I/air, transport coefficient and thermodynamic properties were also investigated, and the result showed that around 30% content of CF_3I may be used as a possible substitute [53].

C_5-PFK, C_6-PFK, and mixture were analyzed for arc quenching and insulating properties by ASEA Brown Boveri (ABB) is a Limited Company (Multinational Corporation) and encouraging results were found [54-57]. C_5-PFK with N_2 and O_2 for medium voltage and C_5-PFK with CO_2 and O_2 for HV GIS were recommended. HV GIS with rating

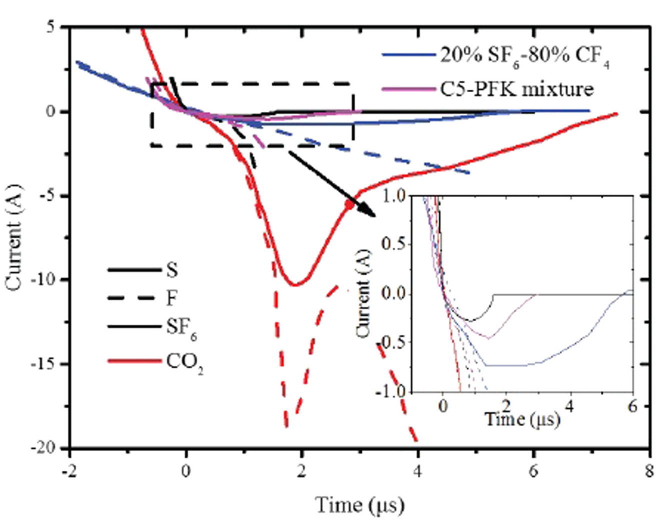

Fig. 6. Comparison of post arc current of CO_2, SF_6, and mixture 20%SF_6–80% CH_4 (S: Success , F: Failure) , [46-48].

170 kV/31.5 kA and medium-voltage switchgear 22 kV/1600 A for feeders and 22 kV/2000 A for bus bars have been installed and operating satisfactorily in Germany and Switzerland since 2015 [52, 57]. Post arc current measurement was carried out with a self-blast live tanker breaker and found that peak/maximum value of post arc current is very near to SF_6. Table II summarizes the post arc current peak values and duration of different gases.

Typically, Vermeer's constant is used to comprehend heat dissipation capability, and to do so, temperature rise test was conducted on 420 kV bus bar keeping pressure as 5.5 bar and operating temperature as -25°C. The constant for heptafluoroisobutyronitrile was determined to be 13.8, higher than SF_6 while the constant for green gas, mixture of heptafluoroisobutyronitrile and carbon dioxide (C_4F_7N/CO_2), was little lower than that of pure SF_6 but still better than CO_2 [17].

D. Partial Discharge and Flashover

Natural gases when mixed with other gases improve partial discharge characteristics, for example, partial discharge properties were found better for mixture (CF_3I/CO_2) than (SF_6/CO_2), but it demands a higher ratio. To get exceeded level than SF_6, the weightage of CF_3I in CO_2 must be 30%/40% [4, 58]. It was also found that inception voltage (+) is better for (CF_3I/CO_2) than that of (CF_3I/N_2) [59], and so, it was concluded that the synergistic effect in terms of inception voltage is higher for CO_2 as compared to N_2.

Unlike other gases, C_5-PFK decomposition process is irreversible during arc, discharge, or thermal decomposition. Partial discharge test on C_5-PFK was performed [60], and it was found that decomposed products do not recombine to their original structure, and some of the by-products were also toxic.

Partial discharge (PD) test has also been carried out on mixture C_4F_7N/CO_2 in 4%/96% ratio, and it was found that inception voltage is around 0.76–0.84 of SF_6 with longer rising time and pulse width PD pulses [61]. So from PD viewpoint, it requires higher pressure or increased content of C_4F_7N (3M™ Novec™ 4710 dielectric fluid) to meet the requirement of SF_6; however, those studies are not available yet. Recently some research has been carried out to present model for discharge process. Discharge of flowing gases includes three basic phases : a) deflection of the main discharge path, b) blowing away of some electrons, and c) decrease in gas density [63]. This modeling will enable the researcher to calculate breakdown voltage.

Solid material–gas interaction is another important factor to be discussed especially for usage in GIS as linked insulation fails at

TABLE II.
POST ARC PEAK CURRENT AND DURATION [46-48]

Gases	Post Arc Current Peak (A)	Duration (µs)
SF_6	0.272	1.59
C_5F-PFK mixture	0.457	2.94
SF_6/CH_4–20%/80%	0.742	5.81
CO_2	10.3	7.42

lower voltage due to flashover in solid material. Pure N_2, CO_2, and air exhibit very lower flashover characteristics as compared to SF_6; however, the trend is much similar. And adding SF_6 to natural gases improves their flashover voltages [64], as shown in Fig. 7.

Flashover characteristics were found better for (CF_3I/N_2) for 30%/70% ratio than that of (SF_6/N_2) for 20%/80% [65] under AC and impulse voltage both, though it had slightly lower dielectric strength. Study of surface flashover for (C_4F_7N/CO_2) has been carried out [66], with epoxy insulator, and it was found that (C_4F_7N/CO_2) with ratio 13%/87% exhibits almost 0.8 times of SF_6 flashover voltage and that further increase in the content of (C_4F_7N) can lead to saturation of surface flashover [66].

III. DISCUSSION

There are also some other necessary aspects to be discussed such as boiling point, decomposed by-products, and toxicity. SF_6 has boiling point (−64°C), though it is sufficient for most of the applications but still high as compared to natural gases such as N_2 (−196°C), air (−194°C), and CO_2 (−79°C). [15]. Compressed air, CO_2, and N_2 have been successfully implied up to 145 kV switching devices as insulating medium [67], but to use natural gases, more volume or high pressure is required to meet the required electrical dielectric strength which leads to a significant increase in size and cost, undesirable for design consideration. That is why natural gases are preferred for mixture as buffer gases to reduce overall boiling point.

Boiling point of some gases is depicted in Table I, which shows that fluoroketones have very high boiling point, limiting their usage in icy/snowy zones. C_6-PFK has boiling point of 49°C and C_5-PFK has 27°C, which means it liquefies under standard conditions. However, it can be used with a mixture of N_2 or air. GIS 145 kV was tested for withstand voltage with air and C-PFK, and results were encouraging [17, 18], but the decomposition process is irreversible during arc, discharge, or thermal decomposition for C_5-PFK [68, 69] and also for

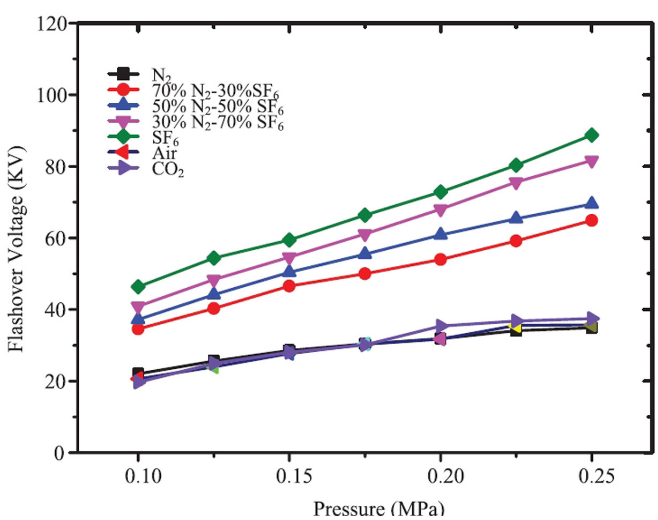

Fig. 7. Flashover comparison of different gases [66].

($C_6F_{12}O/CO_2$) mixture [70], so properties will differ prior and post arc state which limits its usage in GCB.

CF_3I despite its good insulating properties has a higher boiling point of about −22.5°C, which means this gas cannot be used alone and hence mixing with natural gases is recommended. There is another issue associated with CF_3I, that is, its by-products such as C_2F_6, C_3F_6, C_3F_8, CHF_3, and C_2F_5I are toxic [71-73]. Gas itself is categorized as carcinogenic and mutagenic that will be risky to be utilized, due to health hazard issues.

Dichlorodifluoromethane (R_{12}) and tetrafluoroethane (R_{134}) also have higher boiling point at atmospheric pressure, such as −29.8°C and −26.3°C, respectively [19, 20]. This was similar with that of CF_3I and hence mixing with natural gases is recommended. However, the mixture will have its own limits because of the lower dielectric strength of natural gases. Issue with R_{12} is that it contains chlorine that causes ozone depletion [19]. R_{134} has an issue of self-recoverability as AC power frequency breakdown tests show that after tenth shot, breakdown voltage comes down very quickly because of carbon deposit formation on the electrode [20].

(C_4F_7N) has very high boiling point of about −4.7°C [17, 41], and its by-products during decomposition process are C_3F_7, C_3F, CN, CNF, CF, CF_2, CF_3, CFCN, F, free radicals, and CF_4 [74]. Some free radicals recombine to produce C_2F_6, C_3F_8, CF_3CN, CO, and CF_4, some of which are low toxic compounds. However, the addition of CO_2 lowers its boiling point, and less decomposed products are generated [75]. In pure (C_4F_7N) at 2400 K, products were about 96%, while these were reduced to 58% in (C_4F_7N/CO_2) mixture [75].CF_4 and C were very much reduced and precipitate carbon formation was avoided, so green gas (C_4F_7N/CO_2) is a better option than pure (C_4F_7N). Another mixture of ($C_4F_7N/N_2/O_2$) has also been tested, and less solid precipitate was produced with much better dielectric performance [76, 77]. However, toxicity assessment of (C_4F_7N) and its by-products recommends taking measures for eye safety and respiration [78].

IV. CONCLUSION

From the discussion, it is obvious to conclude that natural gases are classified as an excellent choice for mixture component to reduce boiling point, attain lower GWP and better arc-quenching capabilities (especially CO_2 in terms of arc quenching). Trifluoroiodomethane despite considerable dielectric strength and decent arc-quenching capabilities with a mixture of natural gases will be risky to be utilized, due to health hazard issues as being carcinogenic and mutagenic gas. Dichlorodifluoromethane (R_{12}) and tetrafluoroethane (R_{134}) suffer the problem of ozone depletion and self-recoverability issues, respectively. Perfluoroketones, especially C_5-PFK, has a good potential for replacement, but irreversible decomposition process and high liquefaction temperature are still hindrance in complete replacement. Thus, heptafluoroisobutyronitrile (C_4F_7CN) is the one that has upright potential to replace SF_6 as it has wonderful dielectric strength and moderate global warming potential. Adding CO_2 enables to get much lower GWP level, lower liquefaction point, better arc-quenching ability, and much reduced decomposed products are obtained. So green gas, as labeled to mixture (C_4F_7CN/CO_2), is declared to be the best replacement for SF_6 at the time.

V. FUTURE WORKS

Though (C_4F_7CN) has shown a remarkable potential to replace SF_6, it is at the initial stages of research, and much deep study is still required to replace it completely. Studies for compatibility with other materials have been started to investigate, but very few studies have been conducted for streamer radii and leader propagation. Basic physical properties, electron transport coefficients, and radiation properties of relatively new gases must also be investigated. Much study is needed to find an optimum compromise among insulation performance, environmental concerns, health issues, safety concerns, and liquefaction temperature.

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