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Article

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Research paper

A review on SF₆ substitute gases and research status of CF₃I gasesSong Xiao^{*}, Xiaoxing Zhang, Ju Tang, Siqi Liu

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ABSTRACT

SF₆ gas is widely used in electric power apparatus as an insulation and arc-quenching medium. However, the application of SF₆ gas faces two serious problems, including the heavy global warming effect and high toxicity of its decomposition products. So, scholars committed to finding environmental-friendly alternative to SF₆ gas and the relevant research results have been obtained. As an insulating or extinguishing medium, conventional gases, SF₆ gas mixtures and electronegative gases and mixed gases exhibit different strengths and disadvantages. The current research progress of the main alternative gas has been summarized in this paper. And that is summarized in detail in terms of physical and chemical properties, insulating properties, arc characteristics, mechanism and the scope and limitations of different alternative gas in engineering applications are analyzed. Meanwhile, we forecast the development prospects of environment-friendly gas insulation, and theoretically analyzed CF₃I, which has the potential to replace SF₆. Finally, we analyzed the current application feasibility and scope of CF₃I, and pointed out the further research direction.

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1. Deficiencies of SF₆ as insulating gas

In the 21st century, global energy production and consumption continue to grow, and a significant amount of fossil energy is developed and utilized, thereby resulting in resource constraints, environmental pollution, climate change, and other global problems that pose a serious threat to human survival and development. In recent years, haze and other environmental problems have raised new questions regarding energy restructuring. Thus, the road to sustainable development has been taken. Developing the power industry has become a key factor to resolve economic development and environmental conflict issues. In the context of rapid development of electric power, high-voltage electrical equipment is an important link in a power system (Xiaoxing et al., 2016).

1.1. Use of SF₆-insulated electrical equipment

The proportion of gas-insulated electrical equipment in high-voltage electrical equipment rises annually. In 1937, the French first used sulfur hexafluoride (SF₆) as an insulating medium for high-voltage electrical equipment. The high-voltage electrical field has experienced a major revamp and rapid development. In the 1960s, the United States produced the first gas-insulated switchgear (GIS), which used SF₆ gas as insulating medium. Since SF₆ GIS was operated in Germany for the first time in 1967, it

has been rapidly and widely used in high-voltage power and in high-voltage power system, extra high-voltage power system and ultra-high-voltage power system because of its high reliability, low maintenance cost, small footprint, and flexible configuration (Chu, 1986; Christophorou et al., 1997; Tominaga et al., 1981). Gas-insulated transformers (GIT), gas-insulated lines (GIL), gas-insulated circuit breakers (GCB), cubicle-type gas-insulated switchgear (C-GIS), and other SF₆-insulated equipment are widely used in power systems with the development of technology. In the Chinese power equipment industry, SF₆ demand reached 5000 tons in 2010 from only 820 tons in 2001 (Mingliang, 2010). The great development of the power industry brought the high-voltage electrical equipment industry to a golden period for more than 10 years. However, it also led to the rapid increase in the use of SF₆ (Table 1).

1.2. Greenhouse effect of SF₆

SF₆ gas is considered as one of the most harmful kinds of atmospheric greenhouse gases (Xiaoxing et al., 2013b). Its global warming potential (GWP) is 23,900 times higher than that of CO₂, and the life span of this gas is 3400 years in the atmosphere (Xiaoxing et al., 2013b). Global warming, ozone depletion, and drastic reduction of biological species are known as the three major environmental problems. Humans are not threatened by short-term greenhouse effects. However, global warming caused by climate change is bound to have disastrous consequences to human conditions in the long run. SF₆ gas in the atmosphere has an annual growth rate

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Table 1
Newly installed capacities of electric power supply over the years and trend prediction of SF₆ demand quantity.

Year	New capacity / million kW	Annual demand of SF ₆ / t
2001	15	820
2002	22	930
2003	34.8	2300
2004	51	2800
2005	66.02	3500
2006	105	4500
2007	115	4500
2008	90.51	4800
2009	89.70	5200
2010	85	5000
2011–2020	55–60	4500–5500

of 8.7% (Hong, 2006). At present, SF₆ gas accounts for more than 15% of greenhouse gas emissions. The Kyoto Protocol, which was signed by several parties during the United Nations Convention on Climate Change in 1997, lists SF₆ as one of the six greenhouse gases that are restricted for use, thereby limiting the use of SF₆ gas. California proposes gradually reducing the amount of SF₆ in electrical field starting in 2020. In 2014, the European Union planned to reduce SF₆ emissions by two-thirds by 2030 (Mota-Babiloni et al., 2015). On the contrary, discussions in International Council on Large Electric systems (CIGRE) determined that SF₆ has obviously become one of the major causes of power development and environmental protection.

In the electric power industry, high-voltage switchgear accounts for SF₆ gas consumption of more than 80%, whereas approximately one-tenth is consumed by the medium-voltage switchgear. Mainly used in 126–252 kV high voltage, 330–800 kV EHV fields, particularly in 126, 252, and 550 kV GCB, GIS, C-GIS, and GIL (Yanabu et al., 2001). Reasonable and correct use of SF₆ gas reduces emissions to a nonregulation point. Natural Resources Defense Council, an environmental organization that compares the climate commitments of all countries, believes that the commitments of the EU, US and China can be ranked in the world's top three. However, these three countries are also the major emitters of greenhouse gases in the world (Min, 2015). Thus, they need to limit the use of greenhouse gases, particularly SF₆.

SF₆ enters into the atmosphere through normal leak, commissioning, maintenance, and SF₆ gas recycling. At present, measures to reduce SF₆ emissions include the following: the regular use of advanced SF₆ leak detection equipment to detect leakage in SF₆ gas-insulated equipment and the timely use of advanced materials to plug the leak site (Rui et al., 2009), research and application of SF₆ gas recycling technology, and the use of SF₆ gas mixture instead of pure SF₆ gas. These measures may reduce SF₆ emissions to a certain extent, but they cannot eradicate hidden dangers. Looking for an environmentally friendly alternative to the insulating medium of SF₆ with an electrical equipment should not be delayed. Reduction and substitution of SF₆ are urgent problems that must be solved in the electrical switch industry. They are also unavoidable responsibilities and obligations in power-switching equipment research and manufacturing field.

1.3. Toxicity of SF₆ and its decomposition products

SF₆ and electrical equipment commonly use metals because other organic materials do not chemically react. However, in a high-power arc, spark discharge and corona discharge, products such as SF₄ are emitted when SF₆ breaks down. SOF, SOF₂, SO₂F₂, and other toxic substances can be generated when SF₄ reacts with oxygen in electrical equipment. With water inside, SF₄ reacts and generates not only H₂SO₄ and HF, which cause insulation, breaking performance degradation, and corrosion of parts, but

also HF, SO₂F₂, SOF₂, SO₂, and other toxic substances. SF₆ and its decomposition products generate WF₄, AlF₃, CuF₂, and other toxic substances when they react with copper tungsten alloy electrode, copper, aluminum, and other metal materials, thereby affecting the properties of metallic materials. Insulating material reacts with toxic products, such as epoxy phenolic glass insulating member that contains silicon component or quartz sand. Epoxy resin casting parts use glass as filler. Silicone rubber and grease set off a chemical reaction, thereby producing SiF₄, Si(CH₃)₂F₂, and other products (Bin, 2006).

Other substances cause corrosion in insulation equipment, thereby causing insulation accident risk and affecting the reliability and normal operation of a power system. In addition, toxic products pose risks to the health of workers, which may even be life threatening. SF₆ is a simple asphyxiating gas. Contact with this gas may accelerate breathing rate and heart rate. The gas can also slightly affect muscle coordination, and it can cause emotional irritability, fatigue, nausea, vomiting, and other symptoms. Repeated exposure to high levels of SF₆ may cause fluorosis and dental fluorosis, and nausea, vomiting, loss of appetite, diarrhea, or constipation may be experienced. Nosebleeds and sinus problems may also occur. Under normal circumstances, SF₆ gas contains oxyfluorides. Hydrolyzing these gas can generate HF, SO₂F₂, SOF₂, S₂F₁₀, and other substances. These substances are strong irritants and directly endanger human health. Moreover, S₂F₁₀ is highly toxic (Yafen et al., 2006). The summary of clinical symptoms caused by SF₆ by-products is shown in Table 2 (Luwen, 2004).

The health damage caused by SF₆ and its by-products obviously exist. In 1990, Kraut and Lilis reported six workers who contacted SF₆ decomposition products in an appliance repair facility; the workers were exposed without protection in a closed space for more than 6 h (Kraut and Lilis, 1990). The initial symptoms included shortness of breath, chest tightness, coughing, eye and nose irritation, headache, fatigue, nausea, and vomiting. These symptoms diminished after termination of contacting with gas, but the symptoms of four of the six workers lasted for a month. Lung imaging showed the temporary discrete sheet atelectasis of one of the workers. Moreover, slight diffuse infiltration on the left lower lobe appeared on a worker. Pulmonary function tests showed that one worker had transient obstructive changes. The result of the examination was normal after a follow-up one year later. In 1988, Pulling and Jones reported two workers who entered a high-voltage circuit breaker equipped with a tower (Pilling and Jones, 1988). The circuit breaker had SF₆ concentration of 1500 ppm and SO₂F₂ concentration of 50 ppm. The workers experienced dyspnea, hemoptysis, cyanosis, and other symptoms. For the safety of power line workers, a nontoxic alternative to SF₆ gas must be used to avoid the recurrence of the aforementioned incidents.

Therefore, SF₆ use in electrical equipment aggravates greenhouse effects. It also has security implications for power line workers. Searching for safe, reliable, environmentally friendly, and high-performance insulation alternative gases is necessary, and their use must be promoted.

2. Development history and current situation of SF₆ alternatives

In 1900, SF₆ gas was first synthesized directly with elemental sulfur and fluorine by Lebeau and Modsson from Université de Paris, France. SF₆ is a non-combustible gas with good insulating properties and quenching arc performance. By 1938, Cooper from American suggested it as an insulating medium. In the same year, V. Grosse from German has proposed SF₆ as arc media of the high-voltage circuit breaker. SF₆ gas was supplied commercially in 1947. Until 1955 the world's first SF₆ circuit breakers was made by Westinghouse Electric Corporation and put into operation in

Table 2Main clinical symptoms caused by toxic decomposition products of SF₆.

Decomposition gas of SF ₆	Clinical symptoms
SF ₄	It can cause lung damage, which affects the respiratory system; its toxicity is similar to phosgene toxicity.
S ₂ F ₁₀	Its toxicity is greater than phosgene toxicity; the respiratory system is mainly damaged, which may result in pulmonary edema.
SOF ₂	It can cause severe pulmonary edema and mucous membrane irritation.
SO ₂ F ₂	Inhalation of this odorless gas can quickly result in death.
SOF ₄	It can cause lung damage.
HFSO ₂	It has a strong stimulating effect on the skin and mucous membranes; it can cause water in lungs, mucous membrane irritation, swelling, pneumonia, and respiratory system damage.

the 115 kV grid. Since then, SF₆ has been widely used in various types of high-voltage electrical equipment as insulating medium. Due to strong electronegativity, high stability and excellent thermal conductivity, even to this day, SF₆ is still the insulating gas with the most extensive range of application and the maximum usage.

2.1. Research on SF₆ mixture

Since the 1970s, the research on SF₆ gas mixture as an insulating material has gradually expanded. The primary purpose of the research is to solve the issue in extremely cold areas, where SF₆ could easily liquefy. SF₆ is expensive and sensitive to nonuniform electric field and other issues. The international discussion on SF₆ mixed gas began in the 1950s (Lingal et al., 1953). During the 1970s, scientists at the University of Windsor applied direct current, alternating current, and pulse voltage breakdown in a uniform and nonuniform electric field to study the breakdown characteristics of SF₆ (with air, N₂O and N₂) gas mixture. The dielectric strength of a SF₆/N₂ (including 50%–60% SF₆) mixed gas can reach 85%–90% of pure SF₆, and it can increase the breakdown strength in pulse and a nonuniform electric field. An 800 kV transmission line that uses mixed gas costs only 21% of pure SF₆, and the pressure of which can be higher than the SF₆ pressure of 600 kPa (Malik and Qureshi, 1979).

In the 1980s, Qiu Yuchang from Xi'an Jiao Tong University led a team to study the insulating properties under different field conditions of SF₆ and air, N₂O, N₂, CO₂ and other hybrid gases. The team collaborated with domestic manufacturers to develop a hybrid SF₆ GIT, capacitor, switchgear, and other electrical equipment (Yuchang and Yunping, 1993; Yuchang and Dengming, 1994). Zhao Hu and Li Xingwen of Xi'an University studied the insulation characteristics of SF₆/CF₄ mixed gas (Hu et al., 2013b). SF₆ mixed gas was also applied as an insulating medium power equipment in actual engineering. The world's first SF₆/N₂ mixed gas-insulated transmission line operated in the early 2000s in the international airport of Geneva, Switzerland (Koch and Hopkins, 2005). Electricite de France (EDF) works with Asea Brown Boveri Ltd. (ABB) to develop long-range SF₆/N₂ gas mixture GIL to eliminate the negative effect of overhead transmission lines on the environment and to lessen SF₆ in the mixed gas by 30% by replacing the 420 kV overhead transmission line in France (Diessner et al., 1999). At present, many scholars are studying SF₆ gas mixture. The demand of high-voltage equipment based on the DC in the power system construction is gradually increased. Scholars at North China Electric Power University investigated the SF₆/N₂ gas mixture in the DC voltage affected by metal particles and liquefaction temperature issues (Youping et al., 2015b). The promotion and use of SF₆ mixed gas-insulated electric equipment can reduce the use and SF₆ emissions to a certain extent.

2.2. Research on electronegative gases and mixtures as SF₆ substitute

Although SF₆ gas mixture can reduce the use of SF₆ to a certain extent, using the latter in high-voltage equipment cannot be completely avoided. Thus, scholars began searching for an insulating gas substitute for SF₆. Its physical and chemical properties must be determined according to the structural characteristics to meet or exceed SF₆ insulating properties. Gases with similar characteristics must be determined as well. SF₆ is an electronegative gas. The attached cross section is relatively large, and the electron can be easily absorbed into the anion. The moving speed of the anion is considerably smaller than that of electrons. Complex reaction between anion and ion may occur easily. Thus, charged particles in gas are greatly reduced, thereby causing difficulty in the formation and development of discharge. In addition, electronegative gas molecular usually is so large that its free path is short. Sufficient energy cannot be obtained easily. Thus, collision ionization cannot occur effectively, thereby increasing the electric strength of SF₆. Therefore, stable, nontoxic electronegative gas molecules can be used as an alternative because of their advantage in physical properties.

In the 1980s, Devins studied the breakdown voltage of certain electronegative gases such as CF₄, C₃F₈, C₄F₁₀, and C₂F₆. These gases are ranked as follows according to their insulating properties: C₆F₁₄ > C₄F₁₀ > C₃F₈ > C₂F₆ > CF₄ (Devins, 1980). In the early 1990s, a study (Qiu et al., 1991) determined that CF₂Cl₂ has a dielectric strength similar to that of SF₆, whereas mixed gas CF₂Cl₂-CO₂ has insulation properties similar to those of CF₂Cl₂-N₂ when they are in the same concentration. However, compared with SF₆-CO₂ in the same concentration of electronegative gases, the insulation properties are different. In the late 1990s, the problem of greenhouse effect worsened; thus, the electrical field research opened a new chapter on new alternative gases. Some hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) gained attention because of their excellent dielectric properties and relatively low greenhouse effect. Takuma In order to solve the problem, Tadasu et al. from Kyoto University investigated the physicochemical properties and insulating property of pure c-C₄F₈. They determined that its insulating property in the uniform electric field is 1.18 to 1.25 times higher than that of SF₆. However, this gas has a high liquefaction temperature and cannot be used in high-altitude areas (Takuma et al., 1999). Yamada Hiroaki et al. from the same laboratory mixed c-C₄F₈ with N₂ to solve the problem. On the basis of streamer theory, the withstand voltage of the mixed gas was studied with Boltzmann equation analysis. This withstand voltage was compared with that of SF₆/N₂ mixed gas (Yamada, 2000). Then, they discussed the insulating properties of three mixed gases, namely, c-C₄F₈/N₂, c-C₄F₈/air, and c-C₄F₈/CO₂, under the ball-board electrode and needle-board electrode. They also studied the possibility of using these mixed gas into GIL. The three mixed gases of c-C₄F₈ have a similar dielectric strength of SF₆/N₂ in the

quasi-uniform electrical field. The dielectric strength is higher than that of SF₆/N₂ in the uniform electrical field. c-C₄F₈/N₂, c-C₄F₈/air, and c-C₄F₈/CO₂ are the mixed gases with synergistic effect (Yamamoto et al., 2001). This research team also studied C₃F₈/N₂ and C₂F₆/N₂ mixed gases in terms of breakdown and partial discharge (PD), and these gases were compared with SF₆/N₂ (Okubo et al., 2002). Xiao Dengming et al. from Shanghai Jiao Tong University recently studied the insulating properties and discharge mechanism of c-C₄F₈ mixed with some buffer gases, such as N₂, CO₂, N₂O, CHF₃, and CF₄. They measured the electronic collapse current in the condition of steady-state Townsend (SST) discharge, and they determined ionization coefficient α , adsorption coefficient η , and effective ionization coefficient ($\alpha - \eta$). Then, they obtained the critical electric strength (E/N)_{lim}. They also compared the results with SF₆ mixed with the same buffer gases. The study showed that the dielectric strength of c-C₄F₈/N₂, c-C₄F₈/CO₂, and c-C₄F₈/CF₄ almost linearly increases with the increase of c-C₄F₈ mixing ratio. The frequency dielectric strength of c-C₄F₈/N₂ is similar to that of SF₆/N₂. The best-mixing ratios of c-C₄F₈/CO₂ and c-C₄F₈/N₂ in AC dielectric strength are 10% and 20%. Compared with c-C₄F₈/CO₂ and c-C₄F₈/CF₄, c-C₄F₈/N₂ and c-C₄F₈/N₂O have advantages in replacing SF₆ when the ambient temperature is above 0 °C. Compared with 10% c-C₄F₈/CO₂/N₂ and 10% c-C₄F₈/CO₂/N₂O, 10% c-C₄F₈/N₂O/N₂ has advantages in replacing SF₆ when the ambient temperature is above -20 °C. These mixed gases are ranked as follows according to their insulating properties: c-C₄F₈/N₂ > c-C₄F₈/CHF₃ > c-C₄F₈/CO₂ > c-C₄F₈/CF₄. Compared with the critical electric field strength of some buffer gases, c-C₄F₈/N₂, c-C₄F₈/N₂O, c-C₄F₈/CO₂, and c-C₄F₈/CF₄ have synergistic effects. However, c-C₄F₈ precipitate carbon atoms in discharging decomposition, thereby reducing the insulating properties of the gas-insulated medium (Liuchun et al., 2008; Biantao, 2007; Liuchun, 2007; Yunkun et al., 2013; Dengming and Yunkun, 2013; Biantao et al., 2006). The Institute of Electrical Engineering of the Chinese Academy of Sciences studied the PD property of c-C₄F₈/N₂ in different atmospheric pressures, ratios, and electrode distances. The findings proved that the initial voltage in PD of the pure c-C₄F₈ is approximately 1.3 times higher than that of the pure SF₆ gas. c-C₄F₈ has a synergistic effect with N₂, and the synergistic coefficient is approximately 0.45 (Weijun et al., 2011). They also studied the decomposition products of c-C₄F₈ and N₂ mixed gas in faults, such as local overheat, PD, spark discharge, and arc discharge. They also discussed the danger of the decomposition products (Kang et al., 2012). Tokyo Electric Power also studied the breakdown characteristics of C₃F₈ and C₂F₆ mixed with N₂ and CO₂. The study showed that mixed gas with 20% C₃F₈ and 80% N₂ shows good characteristics. Researchers from Xi'an Jiaotong University studied and calculated the joint behavior of C₃F₈ at room and high temperature, and they determined that C₃F₈/N₂ has excellent insulating properties at room temperature. It is also far superior to other mixtures of buffer gas and C₃F₈. However, the dielectric properties of C₃F₈ are inferior to those of SF₆ at a high temperature (Wang et al., 2015).

At the 2015 Hanover Fair, Alstom is presenting two first high-voltage applications using g3 (green gas for grid), a gas mixture of C₄F₇N (Novac 4710 fluid) and CO₂ that can replace SF₆ for high voltage air-insulated (AIS) or gas-insulated switchgear (GIS) applications. In August 2014, Alstom became the first company in the world to offer the electrical industry a technically and economically viable alternative to SF₆ (Kieffel et al., 2016). Recently, as the main insulating gas of g3, C₄F₇N have received considerable attention in the field of alternative gases. The dielectric strength of C₄F₇N is 2.74 times that of SF₆ and C₄F₇N is noncombustible and noncorrosive. Its GWP is 2100 and its ozone depletion index (ODP) is 0, indicating it is not destructive to the atmosphere. At the same time, its toxicity is very low (Kieffel et al., 2016). The performance of C₄F₇N is good in terms of insulation, environmental protection, and safety.

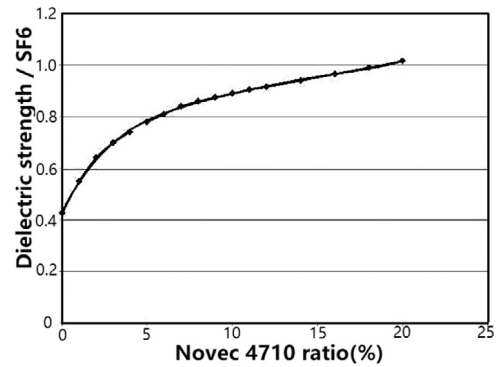


Fig. 1. Dielectric strength master curve for C₄F₇N in mixture with CO₂ (Kieffel et al., 2016).

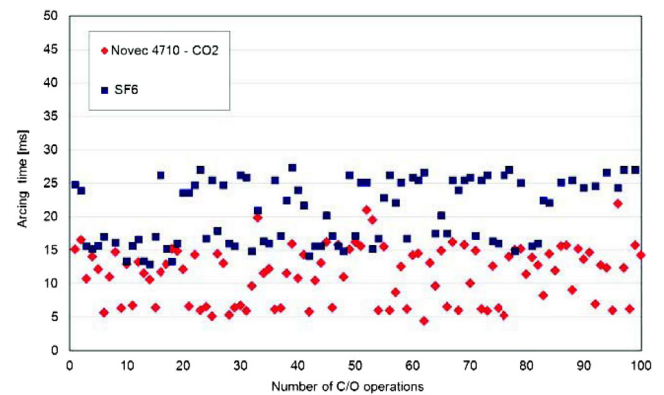


Fig. 2. Arcing time versus C/O operation number on a 420 kV disconnecter for C₄F₇N/CO₂ mixture and SF₆ (Kieffel et al., 2016).

Several achievements have been made in the research on C₄F₇N and its gas mixture. Kieffel et al. conducted tests in 145 kV gas-insulated switchgear equipment and found that an 18%–20% C₄F₇N/CO₂ gas mixture could achieve the same insulation strength as pure SF₆, which is showed in Fig. 1. They also tested a 4% content C₄F₇N gas mixture 100 consecutive times and found that the average arcing time of the C₄F₇N gas mixture is 12 ms, which is shorter than that of SF₆ (15 ms) at the same pressure (Fig. 2) (Kieffel et al., 2016). Nechmi et al. measured the breakdown voltage of a C₄F₇N/CO₂ gas mixture with different electrodes under 50 Hz alternating current (AC) and lightning impulses. Their test showed that C₄F₇N has the strongest synergistic effect with CO₂ at 3.7% concentration (Nechmi et al., 2016). Owens et al. tested the breakdown voltage of C₄F₇N mixed with CO₂, N₂, and dry air at different pressures and concentrations under a plate-to-plate electrode and found that the C₄F₇N/CO₂ gas mixture has the best dielectric strength (Owens, 2016). Preve et al. tested the C₄F₇N/dry air gas mixture and found that its insulation performance is better than that of SF₆ at the impulse voltage, but slightly inferior to that of SF₆ at the AC voltage (Preve et al., 2016). These studies confirm that the C₄F₇N gas mixture has excellent insulation properties. However, aging occurs in equipment operation.

Scholars completed a comprehensive study on c-C₄F₈, C₃F₈, C₄F₇N and other potential substitute gases (the physical and environmental characteristics is listed in Table 3), and their excellent insulating properties were proved. However, these PFC discharges at high energy may precipitate carbon, and the insulation capacity may be affected. Their performance is easily affected by temperature and electric field conditions, compared with SF₆ instability. Although c-C₄F₈ and C₃F₈ are not typical greenhouse gases,

Table 3

Physical and environmental characteristics of common dielectric gases (Devins, 1980; Yamamoto et al., 2001; Weijun et al., 2011; Kieffél et al., 2016).

Gas	Electric strength relative to SF ₆	Boiling point/° C	Atmospheric lifetime/years	GWP
SF ₆	1	−63	3200	23900
N ₂	0.36	−196	0	0
CO ₂	0.30	−78.5	∞	1
Air	0.30	−183	∞	≈0
C ₂ F ₆	0.78 ~ 0.79	−78	10000	9200
C ₃ F ₈	0.96 ~ 0.97	−37	2600	7000
c-C ₄ F ₈	1.25, 1.31	−6	3200	8700
CF ₃ I	1.23	−22.5	0.005	1 ~ 5
C ₄ F ₇ N	2.74	−4.8	35	2700

their GWP remains high at 8700 and 7000, respectively. Their atmospheric lifetime of survival are 3200 years and 2600 years, respectively. The problem of potential greenhouse problems in insulation gas cannot be fundamentally solved. At this stage, liquefaction temperatures of c-C₄F₈ and C₄F₇N are high (at standard atmospheric pressure of −6 °C and −4.7 °C). They cannot be used in low-temperature high-pressure areas, which limit the development of related equipment manufacturing industry. In addition, the security and toxicity of the decomposition products of C₄F₇N after discharge is unknown, which may be dangerous. Therefore, the feasibility of alternative gases must be explored.

3. Research on CF₃I gases and its mixtures as SF₆ substitute

In recent years, CF₃I has attracted attention in the research field of dielectric materials as a stable and typical electronegative gas. A mixed gas CF₃I with the buffer gas in the physical and chemical properties, thermodynamic properties, and electrical performance is outstanding. CF₃I is also the most promising insulating gas alternative to SF₆ that we have found in recent years. Thus, scholars have been conducting research on CF₃I.

3.1. Physicochemical property

CF₃I is a synthetic gas with a molecule that consists of three fluorine atoms and one iodine atom in the composition of a central carbon atom. A fluorine atom is the highest electronegative atom in nature; an iodine atom and a carbon atom have relatively high electron affinity (+295 kJ/mol and +122 kJ/mol) (Atkins and Jones, 1997). They also have high electronegativity. Therefore, three kinds of atomic electrons, which are easily absorbed, cannot lose electrons easily, thereby reducing the number of free electrons in CF₃I gas and suppressing the generated and developed gas discharge.

CF₃I is the preferred alternative of Halon 1301 as fire extinguishing agent, which was certified by American National Fire Protection Association (NFPA) standard agent. It has been applied widely in the semiconductor etching, blowing agents, and other fields. CF₃I gas is colorless, odorless, and nonflammable (Nakayama et al., 2004; Toyota et al., 2005). It has GWP of less than 5, which is far below that of the SF₆ gas. The atmospheric lifetime of CF₃I gas is only 0.005 years, and its environmental impact is minimal. Its ozone depletion potential (ODP), which is related to placement, is only approximately 0.006 to 0.008 (Kasuya et al., 2009a; Ngoc et al., 2010). The polar bond (C–I bond) of CF₃I is relatively easy to break. Thus, irradiation decomposition may occur in troposphere, and most CF₃I cannot reach atmosphere. Table 4 shows the basic properties of CF₃I and SF₆.

In the normal pressure, the liquefaction temperature of CF₃I is −22.5 °C, which is lower than that of c-C₄F₈ (−6 °C) and higher than that of SF₆ (−63.9 °C). This property is a disadvantage of CF₃I as an insulating gas. The relatively high liquefaction temperature makes the pure CF₃I difficult to use directly, and CF₃I needs to be mixed with buffer gases that have relatively low liquefaction temperature. According to Dalton's law of partial pressures,

Table 4

General properties of CF₃I gas (Taki et al., 2007; Lide, 2004; Mccain and Macko, 1999).

Gas	CF ₃ I	SF ₆
Color	Colorless	Colorless
Odor	Odorless	Odorless
Water-soluble	Trace	Trace
Inflammability	Nonflammable	Nonflammable
Relative molecular mass	195.91	146.05
GWP	<5	23900
ODP	0.006–0.008	0
Atmospheric lifetime (years)	0.005	3200
Liquefaction temperature (0.1 MPa)	−22.3 °C	−63.9 °C
Bond dissociation energy (kcal/mol)	54 (I–CF ₃)	92 (F–SF ₅)
Electron affinity (kJ/mol)	150 ± 20	138
Radiation efficiency (Wm ^{−2} pb ^{−1})	0.23	0.52

the partial pressure of CF₃I is only 0.15 MPa when mixed gas CF₃I/CO₂(30%/70%) is at 0.5 MPa and the liquefaction temperature is below −12.5 °C (Kasuya et al., 2009b). The problem of high liquefaction temperature can be avoided to a certain extent. When the insulating properties are not considered, the mixed gas can meet the majority of the requirements of the insulating equipment.

3.2. Decomposition characteristics and toxicity

Similar to SF₆, CF₃I may produce some decomposition by-products after severe discharge. The destructiveness should be examined to propose targeted countermeasures by studying the product. The major products can be the characteristic components to judge the discharge problems, and the result can be applied to new online insulation monitoring devices in the future. Kyushu Institute of Technology used Gas Chromatography-Mass Spectrometer to examine the decomposition products of CF₃I and the changing trends of the decomposition products under different discharge quantities of PD. They determined that the decomposition products of CF₃I by PD include C₂F₆, C₂F₄, C₂F₅I, C₃F₈, CHF₃, C₃F₆, and CH₃I. CH₃I appears after a certain period in PD. Decomposition products mainly include C₂F₆, which is followed by C₂F₄. Other product contents are low. The content of these products is ranked as follows: C₂F₆ > C₂F₄ > C₂F₅I > CH₃I > C₃F₈ > CHF₃ > C₃F₆. The discharge products increase rapidly and stabilize gradually with the increase of cumulative charge. After PD, except for CHF₃ gas, the content of other products gradually stabilized within a few hours after a small decline. The content of CH₃I fluctuates after a sharp decline, and it cannot be fully restored to its original state after PD (Jamil et al., 2011). Takeda Toshinobu from University of Tokyo studied the decomposition products of CF₃I when a breakdown or insulator surface flashover occurs in a severe nonuniform electric field and in a slightly uneven electric field. They determined that C₂F₆, C₂F₄, CHF₃, C₃F₈, C₃F₆, and C₂F₅I are by-products after a severe discharge. They also determined that C₂F₆ remains as the major product that is independent of electric field uniformity. CF₃I has a strong resiliency. After 1400 times breakdown, the content of

C_2F_6 is only 150 ppm (Takeda et al., 2011). After a long-time severe discharge, trace solid iodine precipitates, namely, I_2 and C_2F_6 , were mainly derived from the chemical reaction: $2CF_3I \rightarrow C_2F_6 + I_2$. Czech Academy of Sciences Institute of Physics studied the process of decomposing atom iodine in glow discharge via oxygen–iodine laser (Jirásek et al., 2011). Russia Troitsk Institute of Innovation and Integration studied and suggested that I_2 is produced primarily by electron collision and dissociation of CF_3I (Kochetov et al., 2009).

C_2F_6 can be produced with high voltage and severe discharge. As an electronegative gas, C_2F_6 has superior insulating properties. However, iodine precipitation may lead to a decline of dielectric strength. After many longtime high-voltage breakdowns that occurs more than 1300 times, the flashover voltage of CF_3I decreases at 11% (Takeda, 2007). Kasuya et al. from Tokyo Denki University proposed to use high purity-activated carbon C_2X as adsorbent to avoid the decline of the insulating properties of CF_3I with iodine precipitation after a long and severe discharge by eliminating the trace iodine vapor generated during discharge (Kasuya et al., 2009a). The content of CF_3I decreases by mixing buffer gases to reduce the probability of C–I bond breakage, which curbs the generation of C_2F_6 and I_2 .

The harmful effect of SF_6 on humans has been confirmed. CF_3I is the most promising alternative of SF_6 ; thus, its toxicity is a wide-ranging concern. According to an animal breathing experiment, CF_3I shows slight toxicity. The Toxicology Committee of the US National Research Council stated the following: human beings in the production, transportation, and storage process will inevitably come into contact with CF_3I . In general, CF_3I has low toxicity, and it causes no harm to the human immune and reproductive systems (Committee on Toxicology, 2004). The committee set 0.2% CF_3I for heart sensitivity as no observed adverse effect level, whereas the lowest observed adverse level is 0.4%.

The median lethal concentration (LC_{50}) of CF_3I to Sprague Dawley rats is approximately 27.4%. A potential health hazard exists in the area of cardiac sensitization following acute exposure to concentrations of CF_3I greater than 0.2%. The effect of CF_3I on reproductive parameters is equivocal. Exposure to CF_3I could possibly be reduced through use of personal protective equipment and engineering methodologies (McCain and Macko, 1999). The standard of the American Compressed Gas Association divides CF_3I into nontoxic gases (Association, 2013). As a discharge decomposition product, C_3F_8 (Perfluoropropane) needs significant attention. If workers inhale a significant amount in a short time, they can experience dizziness, weakness, poor sleep, and other symptoms. Thus, wearing protective gear is important when contacting with C_3F_8 . However, C_3F_8 takes a small proportion in the discharge products in the aforementioned works. A study (Takeda et al., 2009) showed that a flashover discharge only produces 0.00122 ppm C_3F_8 in the uniform electric field and 0.000501 ppm in the uneven electric field. The clinical symptoms caused by the main decomposition products of CF_3I is showed in Table 5.

The minimal content is insufficient to cause harm to humans. Even if CF_3I is characterized by low toxicity, its concentration should be decreased by adding buffer gases to ensure safety.

3.3. Thermodynamic characteristics

In the 1990s, Duan Siyuan et al. from Tsinghua University first studied the thermodynamic characteristics of CF_3I systematically and comprehensively when they examined the substitute of refrigerants. They measured the saturated vapor pressure of CF_3I at the temperature from below the normal boiling point temperature to the critical temperature. They also established a high-precision saturated vapor pressure equation and the vapor state equation. According to the position of the gas–liquid interface disappearance and the critical opalescence strength, they identified the critical

temperature of CF_3I (396.44 K) and its critical density (868 kg/m³). They also identified the critical pressure (3.953 MPa) by calculating vapor pressure measurements, and they measured the saturated liquid viscosity, gas-phase area thermal conductivity coefficient, and speed of sound (Yuanyuan, 1998).

Yokomizu et al. from Nagoya University Japan investigated high-temperature plasma of CF_3I/CO_2 . They determined that the conductivity of CF_3I/CO_2 increases with the increase of CF_3I when the temperature is below 10 kK. Its thermal conductivity is related to CF_3I when the temperature is approximately 7000 K. Its conductance of arc declines when the mass fraction of CF_3I is higher than 0.9 in the mixed gas, and the arc quenching capacity strengthens (Yokomizu et al., 2009). Yann Cressault from Laplace Laboratory in France calculated the equilibrium composition of mixed gas (air/ CO_2/N_2 mixed with CF_3I). Its thermodynamic properties (i.e., mass density, enthalpy, and specific heat) and transmission characteristics (i.e., conductivity, thermal conductivity, and viscosity) were determined and compared with the statistics of SF_6 . The results confirmed that the thermal conductivity of CF_3I was close to that of SF_6 , and the capacities, such as heat conduction and interrupter of CF_3I , could reach the level of SF_6 . The gas mixed by CF_3I and air/ CO_2/N_2 has conductivity lower than that of pure SF_6 , thereby proving that CF_3I and its mixed gases have good breaking capability and are better at inhibiting the production and development of discharge than SF_6 (Cressault et al., 2011). The study on CF_3I and its thermodynamic properties of gas mixture provides a theoretical basis for their engineering application.

3.4. Electrical performance

Before gas is used as an insulating medium for high-voltage electrical equipment. It is necessary to study its insulating properties and main electrical parameters. The insulating properties, including breakdown characteristics, volt–second (V–t) characteristics, PD characteristics, and arc resistance are determined mainly through experiments. CF_3I exhibits good physical and chemical properties, decomposition characteristics, and thermodynamic properties. As a result, it has become one of the most promising alternatives to SF_6 in recent years. Researchers conducted experimental and theoretical studies to expand its insulating properties.

3.4.1. Breakdown characteristics

Toyota and Nakauchi et al. from Tokyo University first used the up-and-down method to measure the 50% breakdown voltage of CF_3I and SF_6 at 0.1 MPa under the rod–board electrode. They determined that when the distance of electrodes is 10 mm, the breakdown voltage of CF_3I is 0.74 times higher than that of SF_6 under positive voltage. However, it is 1.17 times higher than that of SF_6 under negative voltage. Under low pressure, the breakdown voltage of CF_3I is relatively lower than that of SF_6 in spark discharge with low utilization factor of the electric field and the uneven electric field (Takeda et al., 2009). Researchers from Tokyo Denki University measured the 50% breakdown voltage of pure CF_3I , CF_3I/CO_2 , and pure SF_6 by applying the standard lightning impulse voltage under the ball–ball gap (Figs. 3 and 4). The breakdown characteristic of pure CF_3I is 1.2 times as much as that of pure SF_6 . When the content of CF_3I is 60% in the CF_3I/CO_2 mixed gas, its insulating strength can reach the level of pure SF_6 and the insulating strength of mix gas CF_3I/CO_2 (CF_3I/CO_2) is 0.75–0.8 times as much as that of pure SF_6 . The breakdown strength of CF_3I/CO_2 mixed gas increases linearly with the increase of the volume fraction of CF_3I (Katagiri et al., 2008b).

Researchers from the University of Grenoble in France used ball–ball electrode model to simulate the quasi-uniform electric field to test the DC insulation breakdown characteristics of CF_3I and CF_3I/N_2 gas mixture. At the same mixture ratio, the breakdown

Table 5
Main clinical symptoms caused by decomposition products of CF_3I (McCain and Macko, 1999).

Decomposition gas of CF_3I	Clinical symptoms
C_2F_6	Exposure to < 19.5% oxygen can cause dizziness, coma, increased saliva, unresponsiveness, nausea, vomiting, loss of consciousness and death. Exposed to < 12% oxygen in the atmosphere without any precursors of unconsciousness and loss of self-help. Inhalation of high concentrations of hexafluoroethane mildly suppresses the central nervous system and causes irregular heartbeat. Exposure to its liquid (or rapidly spreading gas) can cause irritation and frostbite.
C_2F_4	Acute poisoning: light cough, chest tightness, dizziness, fatigue, nausea; heavier cases of pulmonary edema and myocardial damage. Chronic poisoning: common headache, dizziness, fatigue, sleep disorders and other neurasthenic syndrome and back pain symptoms. Can cause bone damage
$\text{C}_2\text{F}_5\text{I}$	Irritating to eyes, respiratory system and skin
CH_3I	Causes skin irritation, Toxic if inhaled or swallowed, harmful in contact with skin, May cause respiratory irritation Suspected of causing cancer
C_3F_8	dizziness, weakness, poor sleep, and other symptoms
CHF_3	Suffocation can be caused because it displaces oxygen in the air. Exposed to < 19.5% oxygen in the atmosphere can cause dizziness, drowsiness, increased saliva, unresponsiveness, nausea, vomiting, loss of consciousness and death. Exposed to the atmosphere of < 12% oxygen or less will be without any precursors of unconsciousness and lose the ability to self-help. Inhalation of high concentrations of CHF_3 can mildly inhibit the central nervous system and cause arrhythmia. Exposure to its liquid (or rapidly spreading gas) can cause irritation and frostbite. Prolonged or repeated contact may cause dermatitis. People who previously had heart disease and central nervous system disorders were more susceptible to the effects of overexposure.
C_3F_6	May cause drowsiness or dizziness. Contact with the liquid may cause cold burns or frostbite. Direct contact with the liquefied gas may cause severe and possibly permanent eye injury due to frostbite from rapid liquid evaporation.

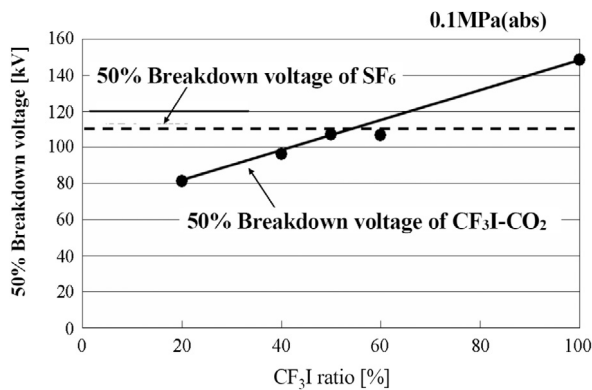


Fig. 3. Breakdown voltage characteristics of $\text{CF}_3\text{I}-\text{CO}_2$ mixture (Positive polarity) (Katagiri et al., 2008b).

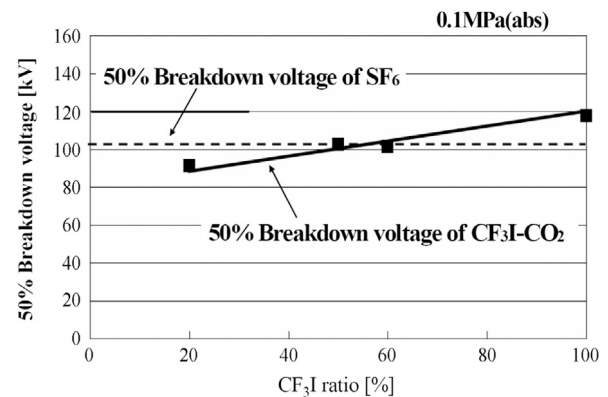


Fig. 4. Breakdown voltage characteristics of $\text{CF}_3\text{I}-\text{CO}_2$ mixture (Negative polarity) (Katagiri et al., 2008b).

voltage of $\text{CF}_3\text{I}/\text{N}_2$ is lower than SF_6/N_2 . The increase of CF_3I ratio results in a linear growth trend of the DC breakdown voltage of the $\text{CF}_3\text{I}/\text{N}_2$ gas mixture; however, SF_6/N_2 exhibits a nonlinear growth trend (Fig. 5) (Ngoc et al., 2009). Takeda from Tokyo University studied the breakdown characteristics of CF_3I in a different electric field. The 50% breakdown voltage is higher than that of SF_6 when the electric field utilization factor is greater than 0.38. Under the uniform electric field, the breakdown voltage of CF_3I is 1.2 times as much as that of pure SF_6 , but it declines to 0.7 under the nonuniform electric field (Takeda, 2008). Researchers from Cardiff University tested the breakdown for the mixed gas under the rod-board electrode, ball-ball electrode, and board-board electrode to

test the influence of the uniformity of electric field to 30%/70% $\text{CF}_3\text{I}/\text{CO}_2$. The result showed that the breakdown voltage of the mixed gas increases with uniformity or long distance of electrodes (Kamarudin, 2013). Tu Youping from North China Electric Power University proved that the insulating property of 30%/70% $\text{CF}_3\text{I}/\text{N}_2$ is similar to that of 20%/80% SF_6/N_2 (Youping et al., 2015a).

The breakdown occurs in the gas and on the contact surface of the gas and solid. Thus, the flashover of gas on the surface of solid should be considered. Takeda et al. studied the insulating properties under the impulse voltage on the surface of pure CF_3I and polytetrafluoroethylene. The first flashover voltage along the surface of CF_3I is 1–1.2 times as much as that of pure SF_6 , and then

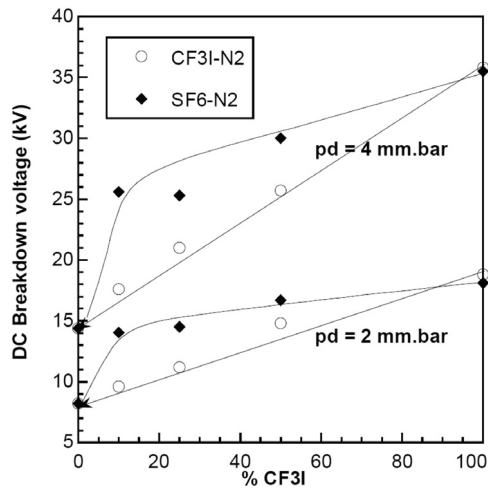


Fig. 5. Breakdown voltage versus CF_3I and SF_6 content in $\text{CF}_3\text{I-N}_2$ and $\text{SF}_6\text{-N}_2$ mixtures, 0.75 mm gap (Ngoc et al., 2009).

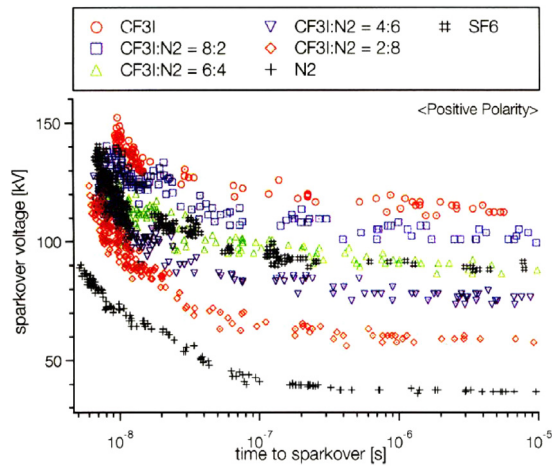


Fig. 6. Positive V-t characteristics in $\text{CF}_3\text{I-N}_2$ gas mixtures at atmospheric pressure (Toyota et al., 2005).

it declines to approximately 0.6 times and remains at that level. Solid iodine precipitates on the interface and influences insulation (Yokomizu et al., 2009).

3.4.2. Voltage–time characteristic

Voltage–time (V–t) characteristic is a way to show the breakdown characteristic, and it is significant in insulation coordination. It is also an important characteristic to evaluate the insulation property. Takeda from Tokyo University compared the V–t characteristics of CF_3I and SF_6 under the condition of 16 ns of the front time and the peak of 200 kV of the impulse voltage. The result showed that the voltage–time characteristic of CF_3I increases with the high use ratio of the electric field. At low use ratio, the V–t characteristic of SF_6 improves (Yokomizu et al., 2009). This team used the same impulse voltage to investigate the V–t characteristics of $\text{CF}_3\text{I/N}_2$, $\text{CF}_3\text{I/air}$, and other mixed gases under the condition of 0.89 of the electric field use coefficient and 10 mm of the electrode distance at the ball–plate electrode. The result showed that when the mix ratio of CF_3I reaches 60%, the V–t characteristic of $\text{CF}_3\text{I/N}_2$ or $\text{CF}_3\text{I/air}$ (Fig. 6) mixture gas is similar to that of SF_6 (Toyota et al., 2005). Compared with SF_6 , the uneven degree of the electric field has a significant effect on the V–t characteristics of CF_3I (Yokomizu et al., 2009).

3.4.3. Characteristics of PD

PD is the early stage of insulation failure of electrical equipment and is a key factor that causes serious fault breakdown. Thus, the characteristics of PD in CF_3I must be studied. Researchers from Kyushu University of Technology measured the PD inception voltage of pure CF_3I and SF_6 in the needle plate electrode. They determined that the negative half cycle initial discharge voltage of CF_3I is nearly equal to that of SF_6 under 0.1 MPa (Kamarol, 2007). Xiaoxing Zhang from Wuhan University examined the PD performance of CF_3I and CF_3I gas mixtures and analyzed the influence of mixture ratio, pressure and electrode spacing factors on the properties of power frequency and PD of the two gas mixtures, namely, $\text{CF}_3\text{I/N}_2$ and $\text{CF}_3\text{I/CO}_2$. The results showed that buffer gases, such as N_2 and CO_2 , can reduce the liquefaction temperature of mixed gases. The PD inception voltage of $\text{CF}_3\text{I/CO}_2$ gas mixture was 0.9–1.1 times as much as that of $\text{SF}_6\text{/CO}_2$ under the same conditions. When the volume fraction of CF_3I was 30%–70%, the PD performance of $\text{CF}_3\text{I/CO}_2$ gas mixture was approximately 0.74 times as much as that of pure SF_6 . When the volume fraction of CF_3I was 20%, the PD inception voltage of $\text{CF}_3\text{I/N}_2$ gas mixture was 0.92–0.94 times as much as that of $\text{SF}_6\text{/N}_2$ gas mixture under the same conditions. The characteristics of PD of $\text{CF}_3\text{I/CO}_2$ gas mixture showed a favorable synergistic effect and the value of synergistic effect was 0.53 (Xiaoxing et al., 2013b,a, 2014).

3.4.4. Arc extinguishing (breaking) performance

Researchers from Tokyo Mechanical and Electrical University studied the breaking performance of CF_3I , $\text{CF}_3\text{I/CO}_2$ and $\text{CF}_3\text{I/N}_2$ gas mixtures in the open close fault (SLF) and at the end of circuit breaker (BTF). They determined that the breaking performance of CF_3I in SLF was 0.9 times as much as that of pure SF_6 . The breaking performance of $\text{CF}_3\text{I/N}_2$ (20%/80%) gas mixture in SLF, relative to that of CF_3I , was closer to that of N_2 , whereas the breaking performance of $\text{CF}_3\text{I/CO}_2$ gas mixture containing the same proportion of CF_3I in SLF can achieve 95% that of pure CF_3I , which is considerably better than that of CO_2 . The breaking performance of CF_3I in BTF was 0.67 times as much as that of SF_6 , and the breaking performance of $\text{CF}_3\text{I/CO}_2$ (30%/70%) gas mixture in BTF was 0.32 times as much as that of SF_6 . The breaking performance of $\text{CF}_3\text{I/CO}_2$ gas mixture containing the same proportion of CF_3I in SLF was nearly the same as that of pure CF_3I . In SLF and BTF, the breaking performance of $\text{CF}_3\text{I/CO}_2$ showed nonlinear growth with the increase of CF_3I mixing ratio, whereas the breaking performance of $\text{CF}_3\text{I/N}_2$ gas mixture exhibited approximately linear growth (Katagiri et al., 2008b,a). Researchers from the University of Tokyo studied the arc quenching performance of CF_3I and its mixed gases in arcing chamber model and calculated the arc power loss coefficient and arc time constant of CF_3I , SF_6 and some buffer gas with Mary formula. The breaking performance of CF_3I and its mixed gases in SLF was also evaluated. The results showed that the relationship of the power loss coefficient (Fig. 7) of each gas was $\text{H}_2 > \text{SF}_6 > \text{CO}_2 > \text{Air} > \text{N}_2 > \text{CF}_3\text{I}$, and the relationship of arc time constant (Fig. 8) was $\text{SF}_6 < \text{CF}_3\text{I} < \text{CO}_2 < \text{H}_2 < \text{Air} < \text{N}_2$. The breaking performance of pure CF_3I in SLF was 0.9 times as much as that of pure SF_6 in the same conditions. The breaking performance of $\text{CF}_3\text{I/CO}_2$ gas mixture showed a favorable synergistic effect, whereas the synergistic effect of the breaking performance of $\text{CF}_3\text{I/N}_2$ gas mixture was not obvious. The breaking performance of $\text{CF}_3\text{I/CO}_2$ gas mixture in SLF was nearly the same as that of pure CF_3I when the mixing ratio of CF_3I reached 20% (Taki et al., 2007).

3.4.5. Study on the mechanism

The free electrons play an important role in the generation and development of gas discharge. Reducing its number and speed and improving the ionization energy can effectively improve the dielectric insulation level and arc extinguishing characteristics.

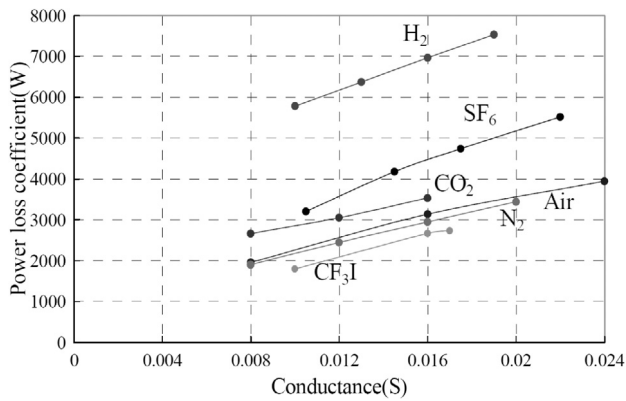


Fig. 7. Conductance–power loss coefficient characteristics of various gases (Nakayama et al., 2004).

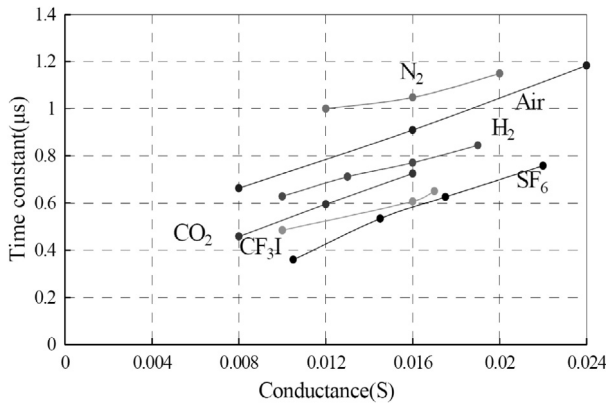


Fig. 8. Conductance–time constant characteristics of various gases (Taki et al., 2007).

Insulating gas molecules should be electronegative to reduce the amount of free electrons. They can adsorb electrons and control the ionization cross section to reduce the supply of free electrons. Reducing the moving speed of free electrons can be convenient for electronic capture. The energy of electron impact ionization should be as high as possible to avoid or curb the development of electron avalanche. The research on discharge mechanism is helpful to analyze the development process of gas discharge current and to determine the effective methods of restraining the breakdown. The scholars study the CF₃I and its mixed gas based on these findings.

For the insulating gas, the smaller the electron drift velocity V_e is, the better its insulating property is. V_e is generally linear with the equivalent electric field (E/N) , E is the electric field (V/cm), and N is the gas density (mols/cm³) (Widger, 2014). Researchers from Hokkaido University calculated the electronic group parameter, electronic drift velocity V_e , and ionization coefficient $(\alpha - \eta)/N$ of CF₃I at critical electric field. The results showed that in the low E/N range, the electron adsorption ability of CF₃I was stronger than that of CF₄, whereas the critical electric field strength $(E/N)_{lim}$ was higher than that of CF₄ (Hasegawa et al., 2009). Urquijo studied the electron drift velocity, effective ionization coefficient, and critical electric field strength parameters of CF₃I and its mixed gases through pulsed Townsend experiment. The results showed that the electron drift velocity of pure CF₃I was slightly lower than that of SF₆, whereas the $(E/N)_{lim}$ of pure CF₃I was 437 Td ($1 \text{ Td} = 10^{-17} \text{ V cm}^2$). It was larger than that of pure SF₆, which was 360 Td. The V_e of CF₃I/CO₂ gas mixture was lower than that of CF₃I/N₂ when CF₃I/CO₂ gas mixture and CF₃I/N₂ gas mixture contained the same proportion of CF₃I (De Urquijo et al., 2007).

Dengming Xiao from Shanghai Jiaotong University also studied the aforementioned parameters by solving the Boltzmann transport equation under the steady-state Townsend (SST) test conditions. He confirmed that the CF₃I/N₂ gas mixture performed better than CF₃I mixed with Ar, Xe, He, N₂ or CO₂. The performance of CF₃I/CO₂ ranked the second (Deng and Xiao, 2014). The variation trend of the electron drift velocity of CF₃I/N₂ gas mixture with the electric field was nearly the same as that of SF₆ and that of CF₃I/CO₂ gas mixture when the CF₃I mixing ratio was higher than 70%. The $(E/N)_{lim}$ of CF₃I/CO₂ gas mixture and that of CF₃I/N₂ gas mixture could attain that of pure SF₆, so could that of CF₃I/CO₂ gas mixture. The when the CF₃I mixing ratio reached 75% (Yunkun and Dengming, 2013). Researchers from the State Key Laboratory of power equipment and electrical insulation at Xi'an Jiao Tong University calculated the α/N , η/N , $(\alpha - \eta)/N$, and $(E/N)_{lim}$ of CF₃I/CO₂ gas mixture and CF₃I/N₂ gas mixture with different CF₃I mixing ratios. They determined that the $(E/N)_{lim}$ of CF₃I/N₂ was larger than that of SF₆/N₂ gas mixture when the mole fraction of CF₃I was larger than 65%. The $(E/N)_{lim}$ of CF₃I/N₂ was larger than that of pure SF₆ when the mole fraction of CF₃I was larger than 70%. The $(E/N)_{lim}$ of CF₃I/CO₂ was larger than that of SF₆/CO₂ gas mixture when the mole fraction of CF₃I was larger than 40% (Hu et al., 2013a).

4. Conclusion

This paper conducts a comprehensive overview regarding research status of SF₆ alternative gases. Research achievements of conventional gases, SF₆ mixed gases and electronegative gases were analyzed. Moreover, the characteristics and research status of electronegative gas CF₃I were emphatically expounded, and main research conclusions of SF₆ alternative gases were summarized below:

(1) There are some applications of conventional gases in practical engineering. As insulating medium, N₂ and air under high pressure can be applied to the low-voltage equipment. CO₂ has some arc extinguishing capability, but it is only applicable for the low-voltage equipment because of the limited breaking capacity.

(2) Mixture of N₂ and a few SF₆, compressed air all can be used as insulating medium in electric power equipment, but insulation strength of those gases is relative low. Besides, in order to keep enough insulation strength, the larger gas pressure and larger equipment volume are required. At the same time, solving leakage and refilling of mixed gases is the main technical problem.

(3) SF₆ gas mixture can basically meet the insulation performance. After being mixed with N₂, SF₆ reduces the liquefaction temperature, which is suitable for cold area. It has been successfully applied in GIL as insulating medium, but this does not completely limit the use and emissions of SF₆ gas.

(4) Electronegative gases generally have high liquefaction temperature, which limit applicable ranges. After being mixed with buffer gases, the overall insulation performance decreased with different degrees, and the types and mixture ratio of the mixed gas are the key factors that affect the dielectric properties. In addition, decomposition characteristics, recombination characteristics, heat dissipation and other properties of mixed gases need further research. Currently, electronegative gases are only studied in the laboratory without engineering practice.

(5) Considering insulation strength, greenhouse effect and other factors, c-C₄F₈, CF₃I, g₃ and so on have great application potential, but related researches are still inadequate. Compared with the SF₆ mixed gas and other potential alternative gases, CF₃I shows great comprehensive strength. CF₃I has attracted significant attention because of its excellent environmental characteristics, relatively stable physical and chemical properties, low toxicity, and excellent thermal conductivity and insulation characteristics, which are even better than those of SF₆. CF₃I and its mixture have great application prospects in low-voltage insulation equipment.

Research trends of SF₆ alternative gases are summarized below:

(1) Pure existing alternative gases show limitations. It can be imagined that multifold gas mixture and gas–solid combination will be used in the future.

(2) At present, there are some achievements and engineering practice on insulation performance of the mixed gases, but no great breakthrough has been made on the study of arc extinguishing performance. Therefore, further exploration on arc extinguishing performance of alternative gases is the focus of future research.

(3) Decomposition properties of electronegative gases and its mixed gas under different operating conditions, insulation defects and trace moisture still need further study. Exploring those decomposition mechanisms and interaction between gases can ensure the safety of engineering practice.

(4) In actual application, the composition of mixed gases will change due to decomposition and leakage. How to detect the medium components accurately and timely, and how to timely fill gases as occasion requires, are urgent technical problems urgent in the application.

(5) When alternative gases are applied in existing equipment, the equipment structure needs to be optimized to satisfy the different insulation demands.

Acknowledgments

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