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Chapter 4

Development Prospect of Gas Insulation Based on Environmental Protection

Dengming Xiao

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Abstract

The research situation of environmentally friendly gas insulation is expounded in this paper. The basic physical and chemical properties of the insulating gases are analysed, to propose several environment-friendly insulating gas of potential alternative to sulphur hexafluoride (SF₆). The insulation characteristics of different components gas mixtures with 90% of nitrogen (N₂) and carbon dioxide (CO₂) as buffer gas and 10% octafluorocyclobutane (c-C₄F₈), Trifluoriodomethane (CF₃I) and heptafluorobutyronitrile (C₄F₇N) as the main insulating gas had been tested with 5–20 mm sphere-plane electrode gaps in non-uniform electric field under the power frequency voltage and positive and negative lightning impulse breakdown. The development prospects of environmentally friendly gas insulation are forecasted. Further analysis of c-C₄F₈, CF₃I and C₄F₇N (some friendly gases, which have the potential to replace SF₆) are conducted trying to points out the further research direction.

Keywords: electrical equipment insulation, environmentally friendly gases, alternatives gases, SF₆

1. Introduction

Because of its good electrical insulating properties, sulphur hexafluoride (SF₆) can satisfy the insulating demands of the electrical apparatus. SF₆ is nontoxic and non-combustible, which guarantees the security of its application in the gas insulating apparatus. What is more, the chemical properties of SF₆ are stable and it can be compatible with most mental and solid insulating materials. There is little decomposing by-products after discharge or arc, which guarantees the following insulating function and protects apparatus. Nowadays, SF₆ has been an important industrial gas with more than 20,000 tons’ produced every year all over the
world, and 80% of that is applied as insulating gas in electrical apparatus [1]. With the continuous increase of China’s electrical demand and the expansion of the electrical grid, the demand for insulating gas will continuously increase [2–4].

Although the characteristics of SF₆ can satisfy the requirements as insulation gas in electrical apparatus, such as gas-insulated substations, scientists have recognised that it can influence and aggravate the greenhouse effect in recent years. SF₆ is a strong greenhouse gas that will cause serious harm to the environment. The Global Warming Potential GWP of SF₆ is 23,900 times stronger than that of CO₂ [5], which means that under the computing period of 100 years. Far more serious is that because of the extremely stable chemical properties, it is very hard to decompose SF₆ in nature and it can exist for 3200 years in atmosphere [6], which will make the environmental influence and greenhouse effect continuously accumulated.

In the Kyoto Protocol to the United Nations Framework Convention on Climate Change signed in 1997 in Kyoto of Japan [2], SF₆ was regarded as one of the six-kinds of greenhouse gas (CO₂,CH₄,N₂O,PFC,HFC and SF₆) and it demanded that developed countries should stop and reduce the total emission of greenhouse gas. With signing the Paris Agreement [3], international society are making efforts to reduce carbon emissions, which means that the application of SF₆ in industry will be limited more and more [4, 5, 7]. Therefore, researching new method of gas insulating to replace SF₆ becomes an urgent work.

It is important to look for environmentally insulating gas with similar insulating characteristics and physicochemical properties of SF₆ to replace SF₆. SF₆ belongs to inorganic fluorinated gases, and its molecular geometry is octahedron with six-fluorine (F) atoms in outer surface and one sulphur (S) atom in centre. Because of fluorine belongs to the halogens, its peripheral electronic layer is occupied by seven electrons and can become stable structure with one more electron, which allows it to strongly attract electron. Moreover, in the molecule of SF₆, F atoms and S atom form more stable covalent bonds by sharing electrons. However, F atoms also have the trend to attract electrons so that the entire molecule has a trend to attract electron. Therefore, it has better insulating characteristics than other gaseous molecular without electronegativity. In addition, although the gas characteristics showed by the structure of macro element cannot show the insulation strength of gas exactly, even counterexample existing, researchers have attached importance to that and the researching emphasis of alternative gas is concentrated on the halogenated gas [8]. In 1997, the research report about the insulation characteristics and arc quenching of alternative gas of SF₆ written by the National Bureau of Standards of the U.S.A [9] introduced many potential alternative gases. Besides, in this work was studied the breakdown voltage under direct current (DC) uniform field of gases, such as organic fluorinated ones, compared with SF₆, and this comparison is shown in Table 1. The result of the report shows that most fluorinated gases have good electronic adsorption, which it is related to the addition of fluorine, but not all the organic fluorinated gases have good insulation characteristics. Besides, it is not correct to evaluate the insulation characteristics just based on the elements that constitute a gas, so it is necessary to analyse different gases in detail for comparison. Because the physicochemical properties of octafluorocyclobutane (c-C₄F₈) are close to SF₆, its cost is low and Greenhouse Warming Potential (GWP) is lower than SF₆, the report has specially indicated that c-C₄F₈ and its mixture can be the study subject for long time [10], so that researchers are focused on the study of this gas.
Besides c-C\textsubscript{4}F\textsubscript{8}, organic halogenated gas, trifluoroiodomethane (CF\textsubscript{3}I), contains fluorine (F) and iodine (I) has been concentrated by researchers for its much lower GWP and better insulation characteristics. At the same time, ALSTOM company in France and 3M company in US produce an electrical insulation gas mixtures together, named G3, whose main ingredient is heptafluorobutyronitrile (C\textsubscript{4}F\textsubscript{7}N), a kind of fluorinated nitrile with Novec 4710 as trade name [11]. Besides, ABB company produces electrical insulation gas mixtures whose main ingredient is fluorinated ketone such as Heptafluoropropyl trifluorovinyl ether (C\textsubscript{5}F\textsubscript{10}O) and Undecafluorohecanoyl Fluoride (C\textsubscript{6}F\textsubscript{12}O). Properties of some potential alternative gases to SF\textsubscript{6} are shown in Table 2.

### Table 1. Relative direct current (DC) breakdown voltages of some fluorination gases [1, 8, 12].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Relative breakdown voltage</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF\textsubscript{6}</td>
<td>1</td>
<td>As reference of gas</td>
</tr>
<tr>
<td>c-C\textsubscript{4}F\textsubscript{8}</td>
<td>0.90</td>
<td>With strong absorption to free electron, especially low-power free electron</td>
</tr>
<tr>
<td>2-C\textsubscript{4}F\textsubscript{8}</td>
<td>About 1.35</td>
<td></td>
</tr>
<tr>
<td>1,3-C\textsubscript{4}F\textsubscript{6}</td>
<td>About 1.50</td>
<td></td>
</tr>
<tr>
<td>Hexafluorobutadiene (2-C\textsubscript{4}F\textsubscript{6})</td>
<td>About 2.3</td>
<td></td>
</tr>
<tr>
<td>CHF\textsubscript{3}</td>
<td>0.27</td>
<td>With weaker absorption to free electron</td>
</tr>
<tr>
<td>CF\textsubscript{4}</td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Relative direct current (DC) breakdown voltages of some fluorination gases [1, 8, 12].

Besides c-C\textsubscript{4}F\textsubscript{8}, organic halogenated gas, trifluoroiodomethane (CF\textsubscript{3}I), contains fluorine (F) and iodine (I) has been concentrated by researchers for its much lower GWP and better insulation characteristics. At the same time, ALSTOM company in France and 3M company in US produce an electrical insulation gas mixtures together, named G3, whose main ingredient is heptafluorobutyronitrile (C\textsubscript{4}F\textsubscript{7}N), a kind of fluorinated nitrile with Novec 4710 as trade name [11]. Besides, ABB company produces electrical insulation gas mixtures whose main ingredient is fluorinated ketone such as Heptafluoropropyl trifluorovinyl ether (C\textsubscript{5}F\textsubscript{10}O) and Undecafluorohecanoyl Fluoride (C\textsubscript{6}F\textsubscript{12}O). Properties of some potential alternative gases to SF\textsubscript{6} are shown in Table 2.

### Table 2. Properties of potential alternative gas to sulphur hexafluoride (SF\textsubscript{6}) [8, 13, 14].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Physicochemical properties</th>
<th>Environmental characteristics</th>
<th>Electrical characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Toxicty</td>
<td>Boiling point (unit: °C)</td>
</tr>
<tr>
<td>SF\textsubscript{6}</td>
<td></td>
<td>Nontoxic</td>
<td>−64</td>
</tr>
<tr>
<td>CF\textsubscript{3}I</td>
<td></td>
<td>Low-toxicity</td>
<td>−22.5</td>
</tr>
<tr>
<td>c-C\textsubscript{4}F\textsubscript{8}</td>
<td></td>
<td>Nontoxic</td>
<td>−6</td>
</tr>
<tr>
<td>g^\textsubscript{3}(C\textsubscript{4}F\textsubscript{7}N/CO\textsubscript{2})</td>
<td></td>
<td>Low-toxicity</td>
<td>24 (Pure)</td>
</tr>
<tr>
<td>C\textsubscript{5}F\textsubscript{10}O/air</td>
<td></td>
<td>Nontoxic</td>
<td>26.9 (Pure)</td>
</tr>
<tr>
<td>Hexafluoropropylene (C\textsubscript{3}F\textsubscript{3})</td>
<td></td>
<td>Toxic</td>
<td>−29.6</td>
</tr>
<tr>
<td>Fluorinated 1,3-butadiene (C\textsubscript{4}F\textsubscript{3})</td>
<td></td>
<td>Toxic</td>
<td>6–7</td>
</tr>
<tr>
<td>Fluorinated 2-butyne (C\textsubscript{4}F\textsubscript{5})</td>
<td></td>
<td>Toxic</td>
<td>−25</td>
</tr>
<tr>
<td>Fluorinated 2-butenone (C\textsubscript{4}F\textsubscript{5})</td>
<td></td>
<td>Toxic</td>
<td>1.2</td>
</tr>
</tbody>
</table>
2. Analysis of potential alternative gas

2.1. Octafluorocyclobutane (c-C\textsubscript{4}F\textsubscript{8})

Octafluorocyclobutane, c-C\textsubscript{4}F\textsubscript{8}, is an important industrial gas. Nowadays, it is used in plasma etching technology or as refrigerant [16]. Similar to SF\textsubscript{6} gas, the performance to absorb electron easily of fluorine in c-C\textsubscript{4}F\textsubscript{8} is shown in the characteristics of the whole molecule, so that c-C\textsubscript{4}F\textsubscript{8} has a stronger absorption to free electron. c-C\textsubscript{4}F\textsubscript{8} is colourless, odourless, nontoxic to human bodies at low concentration, non-combustible, nonexplosive and with GWP of about 8700 relative to CO\textsubscript{2}. Though it belongs to greenhouse, but in the same conditions, its negative effects are just one third of SF\textsubscript{6}[17]. In addition, as organic halogenated gas, c-C\textsubscript{4}F\textsubscript{8} does not contain chlorine or bromine, so it is not harmful to the ozone layer. The molecule of c-C\textsubscript{4}F\textsubscript{8} is circular with a stable chemical structure and does no harm to other solid materials in electrical apparatus, such as aluminium alloy, copper contact and epoxy supporting insulators. Recently, the price of c-C\textsubscript{4}F\textsubscript{8} differs with the purity of gas. The price of this gas with 99.9% purity is about 200 RMB/kg [8] (1 RMB = 0.16 dollar=0.13 euro, the same below), as the price of gas with 99.999% purity is about 500 RMB/kg, and that has obviously reduced compared with the price of about thousand RMB per kilogramme 10 years ago. This is related to more applications, such as refrigerant [18], that are using c-C\textsubscript{4}F\textsubscript{8} and the rise of production. Nowadays, the price of c-C\textsubscript{4}F\textsubscript{8} is only a little bit higher than that of SF\textsubscript{6}, but if c-C\textsubscript{4}F\textsubscript{8} is applied widely in electrical domain, its price still can be reduced, so the cost is not the obstacle to be applied in electrical apparatus.

Long before, Japanese researchers began to research the electrical properties of c-C\textsubscript{4}F\textsubscript{8} and indicated that it had the feasibility to replace SF\textsubscript{6} in electrical apparatus. Then, the researchers of plasma and electric-related domains from the U.S.A. and Mexico began to use Boltzmann equation, calculation of parameter of discharge particle and breakdown test to research the insulation characteristics of c-C\textsubscript{4}F\textsubscript{8}. Shanghai Jiao Tong University, Xi’an Jiao Tong University and other high schools in China began the researches about calculation of academic simulation and breakdown test of c-C\textsubscript{4}F\textsubscript{8}. The results of researches have shown that the insulation characteristics of pure c-C\textsubscript{4}F\textsubscript{8} are better than SF\textsubscript{6} in air pressure at 0.3 MPa and over. The breakdown voltage of the gas mixtures of c-C\textsubscript{4}F\textsubscript{8} and N\textsubscript{2} or CO\textsubscript{2} is higher than the gas mixtures of SF\textsubscript{6} with the same contents, and in low air pressure or atmospheric pressure, the breakdown voltage of the gas mixtures of c-C\textsubscript{4}F\textsubscript{8} can approach the gas mixtures of SF\textsubscript{6} with the same contents. In conclusion, c-C\textsubscript{4}F\textsubscript{8} and its gas mixtures have similar insulation characteristics with SF\textsubscript{6}, and the breakdown voltage differs a little with the composition, mixture ratio and gas pressure, so it can satisfy the demands of actual application.

The relative molecular mass of c-C\textsubscript{4}F\textsubscript{8} is 200, higher than that of SF\textsubscript{6} (146.06), and it means that the condensing temperature of c-C\textsubscript{4}F\textsubscript{8} will be high, is about −6°C, higher than −63.6°C of SF\textsubscript{6}. The insulating gas should exist in gaseous state in the electrical apparatus, thus need to have a low enough liquefaction temperature. One way to reduce its liquefaction point is to add some buffer gas including nitrogen (N\textsubscript{2}) or carbon dioxide (CO\textsubscript{2}), which may lead to a weaker insulation strength. So we need to take a balance between the low liquefaction temperature and good insulation property when considering the mixture ratio for c-C\textsubscript{4}F\textsubscript{8}. 

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gas mixtures. Therefore, c-C$_4$F$_8$ is not suited to be applied in apparatus as pure gas, or it cannot satisfy the demand of arctic alpine regions. Thus, it should be mixed with other gas in some ratios to reduce the condensing temperature of the gas mixtures and be used as gas mixtures.

2.2. Trifluoriodomethane (CF$_3$I)

Trifluoriodomethane (CF$_3$I) is colourless, odourless, non-combustible and nonexplosive. CF$_3$I is a new industrial gas that can be used as an environmental refrigerant and alternative fire-extinguishing agent. It can be used as additive or mixed composition to replace traditional refrigerant Freon and fire-extinguishing material “Halon.” Because its GWP is very low, about 1–5 relative to CO$_2$, is much lower than most organic halogenated gases, so its influence on greenhouse is very small. At the same time, it does not contain chlorine and bromine that is commonly present in most refrigerants, so it will not damage the ozone layer, thus the United Nations regards it as new refrigerant to replace Freon [19]. This can prove that CF$_3$I is a kind of environmentally friendly gas, and has related basis in industrial application. As a kind of fire-extinguishing material, its efficiency is outstanding and has little negative influence on environment, and it is well compatible with normal industrial materials, so that it will not cause chemical reaction or erosion. Therefore, it has passed some related standards of the U.S.A [20], and can be used in aerospace and other areas. In addition, it can rise the security of the electrical apparatus by applying CF$_3$I in electrical apparatus such as cubicle gas insulating switchgear (C-GIS) or compact transformer. It is especially appropriate to be used in populous regions of central city in order to reduce the conflagration or explosion caused by the bug of electrical apparatus. The molecular structure of CF$_3$I is shown in Figure 1 RMB. It is affected by halogens such as F and I, so it has strong absorption to free electron. So that it can absorb free electron at the beginning of discharge when electron avalanche forms, and then it can restrain the formation of collision ionisation, which enhances its insulation property. What is worthy to indicate, that the difference between CF$_3$I and SF$_6$, as well as c-C$_4$F$_8$, comes from the asymmetry of its structure, which makes the polarity effect of the molecule stronger. The three-F atoms in the molecule has stronger absorption to electron than I atom, so the electron cloud in the molecule trends to F atoms, and the density of the electron cloud around the carbon-iodine covalent bond formed by I atom and carbon (C) atom is reduced, and the energy barrier to absorb electron is also reduced. Therefore, the whole molecule has a strong ability to absorb electron.

Because of CF$_3$I is a new industrial gas, its application in China is not widely extended, the production in China is low. Currently, CF$_3$I produced in China costs about 2000 RMB/kg, the price is much higher than SF$_6$ [1]. The main reason why the price of CF$_3$I in China is higher than that for SF$_6$ [1] is that the demand is very low. According to the producers of CF$_3$I (Beijing Yuji Science & Technology Co., Ltd.), after CF$_3$I will be used widely and will be mass-produced, the constant cost of CF$_3$I will reduce a lot with the actual cost lower than 600 RMB/kg. Moreover, by optimising and upgrading, its price will be reduced continuously like that for c-C$_4$F$_8$.

Since year 2000, many researchers in China and abroad begin to research this new insulating gas [21, 22]. Researchers of plasma from Mexico have calculated and measured the ionisation
coefficient, attachment coefficient and electron drift velocity during the process of discharge of CF<sub>3</sub>l and its gas mixtures with N<sub>2</sub>, SF<sub>6</sub> and other gases [23, 24]. The aforementioned work has quantified the reaction between free electron and gas molecule during the process of discharge, and has analysed the insulation strength of gas mixtures from the perspective of the parameters of discharge. Tokyo University of Japan, Tokyo Denki University and Japan Electric Power Company have researched CF<sub>3</sub>l by testing [25, 26]. They make the breakdown test to CF<sub>3</sub>l and its gas mixtures with N<sub>2</sub>, CO<sub>2</sub> and air by using lighting impulse. The results show that the insulation strength of pure CF<sub>3</sub>l is better than that in SF<sub>6</sub>, about 1.2 times than SF<sub>6</sub>, and CF<sub>3</sub>l-CO<sub>2</sub> gas mixtures with high content also has better insulation characteristics to be able to replace SF<sub>6</sub>. Many universities and academies in Europe also research the gas mixtures of CF<sub>3</sub>l-CO<sub>2</sub> and CF<sub>3</sub>l-N<sub>2</sub> in different conditions [24]. The results show that the positive synergistic effect of the gas mixtures of CF<sub>3</sub>l and N<sub>2</sub> is less obvious than that of the gas mixtures of SF<sub>6</sub> and N<sub>2</sub>, which means that in the same mixture ratio, the insulation strength of the gas mixtures of CF<sub>3</sub>l-CO<sub>2</sub> cannot increase with the rising content of CF<sub>3</sub>l because of the synergistic effect [22]. In addition, the gas mixtures of CF<sub>3</sub>l and CO<sub>2</sub> with low content show better positive synergistic effect. Shanghai Jiao Tong University, Xi’an Jiao Tong University and Chongqing University in China has researched CF<sub>3</sub>l and its gas mixtures by academic calculation and testing research [27–29]. Shanghai Jiao Tong University uses Boltzmann’s equation to calculate and analyse the discharge parameters and insulation characteristics of the gas mixtures of CF<sub>3</sub>l and N<sub>2</sub>, CO<sub>2</sub>, He and so on and get the alternating current (AC) breakdown voltage in non-uniform electric field and slightly non-uniform electric field by testing [28, 30]. Other researchers have measured partial discharge voltage and other insulation characteristics of the gas mixtures of CF<sub>3</sub>l [31, 32]. The results show that CF<sub>3</sub>l has good electrical insulation characteristics, but the positive synergistic effect of the mixture of CF<sub>3</sub>l and normal buffering gas is not obvious, so that the
insulation characteristics of its gas mixtures are lower than SF\(_6\). Therefore, the research about the synergistic effect of CF\(_3\)I and other gas is the key to be applied in the future.

### 2.3. Fluorinated nitrile gas and G3 gas mixtures

ALSTOM company in France and 3M company in U.S.A. have joined to research the alternative to SF\(_6\) gas. Among many organic fluorinated gases, they choose the gas, which is also alternative refrigerant, and organic chemical compound that contains four-C atoms and seven-F atoms, with a trade name of Novec 4710 [11] and chemical formula of C\(_4\)F\(_7\)N, named G3. Besides, its molecular structure is shown in Figure 2. The gas has replaced a fluorine atom with nitrile group (\(-\text{C}\equiv\text{N}\)) on the basis of the fluorinated hydrocarbon gas, and becomes fluorinated nitrile gas. This nitrile group containing carbon-nitrogen triple bond has a special chemical structure to make C\(_4\)F\(_7\)N have very good insulation performance, which can reach about two-times of that of SF\(_6\). The chemical features of this gas are similar to the organic fluorinated gas with stable chemical characteristics and can be well compatible with other materials used in electrical assets. The relative molecular mass of C\(_4\)F\(_7\)N is 195, with a high condensing temperature of \(-4.7\)°C, so that it cannot replace SF\(_6\) as a single gas, it should become gas mixtures with buffering gas such as N\(_2\) or CO\(_2\). Because of it is a new insulating gas, related testing research is lacking. According to research result obtained by now, the insulation characteristics of its gas mixtures with CO\(_2\) is about 90% of the SF\(_6\) mixtures with the same amount of CO\(_2\) and this gas can also be used as arc quenching medium being applied in circuit-breakers [33]. Nowadays, this gas is researched and produced by 3M company and its cost is dozens of times higher than other gases [33], so the cost is one of the obstacles for its industrial application. With the accomplishment of the production technology of the gas and the development of the producers at home, the price could be reduced.

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**Figure 2.** Molecule structure of C\(_4\)F\(_7\)N.
The gas with the chemical formula of \( \text{C}_4\text{F}_7\text{N} \) has two-isomeric compounds, their chemical formulas and element compositions are the same, but for the different positions of nitrile groups, their molecular structures and microcosmic natures are different. For Novec 4710 gas used in G3 gas, its nitrile group is located in the carbon atom in the middle of the organic carbon-chain, and the other isomeric compound has a nitrile group located in the carbon atom at one end of the carbon-chain, which constitute a virulent gas that cannot be used in industry. In addition, during the production of Novec 4710, by avoiding the production and the mixture of the virulent isomeric compound is key to apply this gas in a real environment. What is more, any gas will be decomposed to produce decomposed by-products in the condition of high temperature and pressure during the discharge process. Moreover, it should be continuously researched about how to guarantee that this gas will not produce toxic isomeric compounds or other gases during the process of discharge or arc interruption.

2.4. Fluorinated ketone gas

ABB company in Switzerland has supported a method for evaluating the greenhouse effect of \( \text{SF}_6 \) \(^{34,35}\), and it is to take advantage of fluorinated ketone gas as the main ingredient of gas mixtures, which contains organic fluorinated gas with carbonyl group (\( \text{C} \equiv \text{O} \)) such as \( \text{C}_5\text{F}_{10}\text{O} \) and \( \text{C}_6\text{F}_{12}\text{O} \). This kind of gas is similar to fluorinated nitrile gas. It is a chemical compound, which uses the carbonyl group to replace one F atom of fluorinated hydrocarbon based on fluorinated hydrocarbon. Because of carbonyl group has carbon-oxide double bond, which is unsaturated bond as the same as the carbon-nitrogen triple bond, it has good absorption to free electron, and it shows higher insulation characteristics in macro-performance \(^{36}\). According to the existing testing data in China and abroad, the insulation characteristics of pure \( \text{C}_5\text{F}_{10}\text{O} \) and \( \text{C}_6\text{F}_{12}\text{O} \) are about two-times higher than \( \text{SF}_6 \) and their GWP value approaches zero, physicochemical properties are stable and they have good compatibility with materials and industrial applicability. The fluorinated carbonyl, which ABB has applied in the gas mixtures has more than five-carbon atoms, so its relative molecular mass is bigger than other insulating gases, such as \( \text{C}_5\text{F}_{10}\text{O} \) with 266 and \( \text{C}_6\text{F}_{12}\text{O} \) with 316. Besides, the condensing temperature of \( \text{C}_5\text{F}_{10}\text{O} \) and \( \text{C}_6\text{F}_{12}\text{O} \) is very high with 24 and 49°C at room condition, which means that they are liquid at normal temperature and gas pressure. Therefore, this gas cannot be used in any electrical insulating domains as single gas, and it can only be applied as gas mixtures. Limited by its high-condensing temperature, it will have low content in the gas mixtures, which causes the limitation of the insulation strength of the whole gas mixtures, so the synergistic effect of this gas and other gas mixtures is very important. Therefore, the use of this kind of gas forming gas mixtures, which allows it keep high insulation characteristics at low concentrations, is the emphasis of research in the future.

3. The power frequency AC breakdown characteristics of the c-\( \text{C}_4\text{F}_{8\gamma\nu} \), \( \text{N}_2 \), \( \text{CO}_2 \) gas mixtures

The breakdown voltage under AC voltage of the gas mixtures with a constant content of 10% of c-\( \text{C}_4\text{F}_{8\gamma\nu} \) and different content of \( \text{N}_2 \) and \( \text{CO}_2 \) has been measured by testing. Figures 3 and 4 show the variety of the AC-breakdown voltage and maximum electric strength of the c-\( \text{C}_4\text{F}_{8\gamma\nu} \), \( \text{N}_2 \), \( \text{CO}_2 \) gas mixtures with the variety of gap distance under different air pressure. The gas discharge test chamber and other internal structure are the same with that in Ref. \(^{37}\). The
method to inflate gas mixtures to test chamber is introduced in Ref. [17]. The gases tested in the present paper are listed in Table 3.

From Figures 3 and 4, it can be observed that the behaviour of c-C₄F₈ mixtures is similar to the SF₆ gas mixtures, the AC-breakdown voltage of the c-C₄F₈, N₂, CO₂ gas mixtures gets higher values as the gap distance gets bigger, and it shows saturation effect. The maximum electric strength of the gas mixtures gets lower values as the gap distance gets bigger, and it shows that the gas mixtures have some sensitivity to the non-uniformity of the electric field. As the non-uniformity of the electric field increases, the maximum electric field able to be tolerated reduces, and the trend of change is similar to SF₆, N₂ and CO₂ in Appendix Figures A1 and A2.

Figure 5 shows that under different gap distances, the variety of the AC-breakdown voltage of the c-C₄F₈, N₂, CO₂ gas mixtures as the gas pressure changes. The AC-breakdown voltage of c-C₄F₈ gas mixtures increases linearly as the air pressure increases without hump effect, and this trend is the same to SF₆ gas mixtures. From Figures 3-5, we can see that the variety of the breakdown voltage of the c-C₄F₈ gas mixtures with the same content as the air pressure and the electrodes gap changes is the same to SF₆ gas mixtures. However, the curves of breakdown voltage of c-C₄F₈ gas mixtures with different contents in the graphs are more concentrated than SF₆. That is to say, the breakdown voltages of gas mixtures have little difference with different contents, at the same time, it shows that the breakdown voltage of the gas mixtures of c-C₄F₈ and CO₂ is the highest and the gas mixtures with N₂ is lower, this is different from the properties of SF₆ gas mixtures. When the gap distance is 20 mm, the AC-breakdown voltage of 10%c-C₄F₈+90%CO₂ is about 10% higher than that of 10%c-C₄F₈+90%N₂.

Figure 3. AC-breakdown voltage of c-C₄F₈, N₂, CO₂ gas mixtures with different gas pressures.
Figure 6 shows under different gas pressures, the variety of the AC-breakdown voltage of the c-C$_4$F$_8$, N$_2$, CO$_2$ gas mixtures as the content changes. If it is make the gas mixtures of 10%c-C$_4$F$_8$ + 90%N$_2$ as the initial matched group, it can be seen that the breakdown voltage of the gas mixtures increases as the content of CO$_2$ increases, and when the content of CO$_2$ exceeds 60%. In other words, with a content of N$_2$ lower than 30%, the increase of the breakdown voltage is more noticeable.

Because of during the process of discharge, N$_2$ will make the ionisation probability of CO$_2$ increase as well, when reducing N$_2$ and increasing CO$_2$ of the c-C$_4$F$_8$ gas mixtures, the breakdown voltage of the triple gas mixtures in Figure 6 does not has an obvious increase.
Figure 5. AC-breakdown voltage of c-C$_4$F$_8$, N$_2$, CO$_2$ gas mixtures with different electrodes gap distances.

Figure 6. Relationship between AC-breakdown voltage and mixing contents of c-C$_4$F$_8$, N$_2$, CO$_2$ gas mixtures.
immediately, and even it has a trend to reduce a little. Only after the content of N\textsubscript{2} is lower than 30% and the content of CO\textsubscript{2} is higher than 60%, the breakdown voltage can increase significantly.

4. Power frequency AC-breakdown characteristics of the CF\textsubscript{3}I, N\textsubscript{2}, CO\textsubscript{2} gas mixtures

To CF\textsubscript{3}I, it has been measured the breakdown characteristics for a constant content of 10\% CF\textsubscript{3}I and with different concentrations of N\textsubscript{2} and CO\textsubscript{2} under AC-voltage applied during the tests. The test method and experiment setup are similar to that in Section 2. The gas mixtures and mixing ratio are listed in Table 1. Figures 7 and 8 show that under different air pressures, the variety of the AC-breakdown voltage applied and the maximum electric strength of the CF\textsubscript{3}I, N\textsubscript{2}, CO\textsubscript{2} gas mixtures as the gap changes. From Figure 7, it can be seen that the breakdown voltage of CF\textsubscript{3}I gas mixtures gets higher as the electrodes gap gets bigger, but curves of different gas mixtures are more approached even closer compared with SF\textsubscript{6} and c-C\textsubscript{4}F\textsubscript{8}. The breakdown voltage of CF\textsubscript{3}I gas mixtures has little difference with different contents of N\textsubscript{2} and CO\textsubscript{2}. Moreover, N\textsubscript{2}, which has better insulation strength, does not perform better than CO\textsubscript{2} when it is mixed with CF\textsubscript{3}I. In Figure 8, the maximum electric strength of CF\textsubscript{3}I gas mixtures has a trend to reduce as the electrodes gap increases, but the curves are smoother than c-C\textsubscript{4}F\textsubscript{8}, which shows that the sensitivity to the electric non-uniformity of CF\textsubscript{3}I is lower than c-C\textsubscript{4}F\textsubscript{8}.

Figure 7. AC-breakdown voltage of CF\textsubscript{3}I, N\textsubscript{2}, CO\textsubscript{2} gas mixtures with different gas pressures.
Figure 8. Maximum electric strength of CF$_3$I, N$_2$, CO$_2$ gas mixtures with different gas pressures.

**Figure 9** shows, under different gaps of electrode, the variety of the AC-breakdown voltage for CF$_3$I, N$_2$, CO$_2$ gas mixtures as the gas pressure changes. Similar to the gas mixtures of SF$_6$ and c-C$_4$F$_{10}$, the AC-breakdown voltage increases linearly as the air pressure increases, and without

Figure 9. AC-breakdown voltage of CF$_3$I, N$_2$, CO$_2$ gas mixtures with different electrodes gap distances.
hump effect or trend of saturation. Curves in Figure 9 are similar to these in Figure 7, the superposition of the curves of gas mixtures with different contents is very high and the performed insulation characteristics are little different.

Figure 10 shows that under different gas pressures, the curves of the variety of the AC-breakdown voltage for CF$_3$I, N$_2$, CO$_2$ gas mixtures changes as the content changes. Generally, with the same mixing ratio of CF$_3$I, the breakdown strength becomes stronger with the increasing ratio of CO$_2$. The same as the judge of the foregoing, the change of the gas mixtures of CF$_3$I is not obvious as the contents of N$_2$ and CO$_2$ change. What is worthy to be concentrated, it is that N$_2$ has higher insulation strength than CO$_2$, but it does not perform in the CF$_3$I gas mixtures.

5. Power frequency AC-breakdown characteristics of C$_3$F$_7$CN/CO$_2$

AC-breakdown characteristics of C$_3$F$_7$CN mixed with CO$_2$ are tested for different concentrations. Figure 11 shows that AC-breakdown voltage of C$_3$F$_7$CN/CO$_2$ gas mixtures varies as the mixture ratio changes between 0 and 10% under different air pressures. Under the same gas pressure, as the mixture ratio of C$_3$F$_7$CN $k$ increases, the AC-breakdown voltage of gas mixtures shows the saturated trend to increase. The lower the gas pressure is, the smaller the growth is. It has to be said that the influence of the mixture ratio $k$ on the C$_3$F$_7$CN/CO$_2$ gas mixtures is less under low gas pressure. In addition, under high-gas pressure, increasing the mixture ratio $k$ can increase the insulation properties of the gas mixtures. When the proportion of C$_3$F$_7$CN increases to 20%, the insulation properties of C$_3$F$_7$CN/CO$_2$ gas mixtures can approach that of pure SF$_6$ under the same condition.
6. Lightning impulse characteristics of c-C$_4$F$_8$, N$_2$, CO$_2$ gas mixtures

Figures 12 and 13 show the testing curves of the positive lightning impulse voltage of gas mixtures of 10% c-C$_4$F$_8$ with N$_2$ and CO$_2$. The positive lightning impulse voltage increases as the electrodes gap increases without the performance of the trend to saturation in SF$_6$ gas mixtures, and the breakdown voltage increases nearly linearly as the air pressure increases. From the perspective of the excitation energy and the ionisation energy of the microcosmic parameters, c-C$_4$F$_8$ is more appropriate to be mixed with CO$_2$ and the positive lightning impulse breakdown voltage of CO$_2$ is higher than N$_2$. According with Figures 12 and 13, it can be

Figure 11. Relationship between power frequency breakdown voltage and mixture ratio of C$_3$F$_7$CN/CO$_2$.

Figure 12. Positive lightning impulse breakdown voltage of c-C$_4$F$_8$, N$_2$, CO$_2$ gas mixtures with different gas pressures.
seen that 10% c-C₄F₈ + 90% CO₂ gas mixtures have the highest breakdown voltage and 10% c-C₄F₈ + 90% N₂ gas mixtures have the lowest breakdown voltage.

Figure 14 shows the different curves of positive lightning impulse breakdown voltage of the gas mixtures of 10% c-C₄F₈ with N₂ and CO₂ as the content of N₂ and CO₂ changes. Because of CO₂ itself has stronger ability to tolerate positive lightning impulse and it will not have obvious ionisation with c-C₄F₈ compared with N₂, the breakdown voltage increases as the content

Figure 13. Positive lightning impulse breakdown voltage of c-C₄F₈, N₂, CO₂ gas mixtures with different electrodes gap distances.

Figure 14. Relationship between positive lightning impulse breakdown voltage and mixing contents of c-C₄F₈, N₂, CO₂ gas mixtures.
of CO₂ in the gas mixtures increases. Because of the high resonance excitation, energy of N₂ in the gas mixtures will have negative impact on CO₂ when the content of N₂ exceeds 30%. The increase of breakdown voltage of the gas mixtures is not obvious, and when the content of N₂ is lower than 30%, the positive lightning impulse breakdown voltage shows more obvious trend to increase as the content of CO₂ increases. Comparing 10%c-C₄F₈ + 90%N₂ and 10%c-C₄F₈ + 90%CO₂, it is not hard to find that 10%c-C₄F₈ + 90%CO₂ has obviously higher positive lightning impulse breakdown voltage.

7. Lightning impulse characteristics of the CF₃I, N₂, CO₂ gas mixtures

Figures 15 and 16 show the curves of the positive lightning impulse (means that the impulse voltage is applied to sphere electrode, and the plane electrode is connected to ground) breakdown voltage of 10% CF₃I with N₂ and CO₂ of different contents. The positive lightning impulse voltage of CF₃I gas mixtures increases with a little saturation as the electrodes gap and air pressure increase. From the difference of breakdown voltages of gas mixtures with different contents and ratios, it can be seen that CF₃I has the similar properties with c-C₄F₈ and it is more appropriate to mix with CO₂.

Figure 17 shows the variation of the positive lightning impulse breakdown voltage of the gas mixtures consisting of 10% CF₃I and N₂ as well as CO₂ as the mixture ratio changes. The curves in Figure 17 have the same change with the c-C₄F₈ gas mixtures, when the content of N₂ is lower than 30%, the excitation energy can weaken the ionisation of CF₃I and CO₂, and the breakdown voltage of the gas mixtures increases obviously and this is the same with the changing trend of c-C₄F₈ gas mixtures.

Figure 15. Positive lightning impulse breakdown voltage of CF₃I, N₂, CO₂ gas mixtures with different gas pressures.
Figure 16. Positive lightning impulse breakdown voltage of CF₃I, N₂, CO₂ gas mixtures with different electrodes gap distances.

Figure 17. Relationship between positive lightning impulse breakdown voltage and mixing contents of CF₃I, N₂, CO₂ gas mixtures.
8. Conclusion

1. In the consideration of insulation strength, c-C$_4$F$_8$ gas mixtures with N$_2$, CO$_2$ is prior than current SF$_6$/N$_2$ gas mixtures and pure SF$_6$. Moreover, c-C$_4$F$_8$ gas mixtures can solves the problem of c-C$_4$F$_8$ gas tending to liquefaction and carbon decomposition. Traditional c-GIS is widely used in the range of middle voltage, mainly in electric power substation and among consumers. Vacuum circuit breaker and grounded switchgear are both installed in a gas cavity shell, which is full with gas at 0.1–0.3MPa. Therefore, c-C$_4$F$_8$ gas mixtures can be applied to the gas switchgear of relative low voltage whose working pressure is low and function is not to break current arc, which can not only guarantee the insulation strength, but also greatly reduce the effect of insulation gas on the environment. Therefore, it has a good potential to substitute SF$_6$ and SF$_6$/N$_2$ as insulation media.

Moreover, for the areas with warm climate, electric apparatus such as transformer and high voltage power transmission wire are promising to use c-C$_4$F$_8$ gas mixtures as insulation media forming gas insulation transformer (GIT), gas insulation line (GIL) and cabinet Gas Insulated Switchgear at middle and low voltage (C-GIS).

2. Above comprehensive of analysis, under the same pressure conditions, the insulating strength of CF$_3$I is higher than that of SF$_6$ while ensuring CF$_3$I not to be liquefied. Compared with compressed air or compressed N$_2$ insulated in C-GIS, CF$_3$I can lower the pressure, in order to reduce the sealing technology and easy to manufacture. The shortcomings of high price also can be relief after mixed with buffer gas. Therefore, using CF$_3$I as insulating gas in C-GIS has better comprehensive performance than that of the present C-GIS.

CF$_3$I and N$_2$ mixed gas can be used as replacement of SF$_6$ gas in the C-GIS at a low pressure, which has bigger advantage on the dielectric strength, liquefaction temperature and cost, especially in 30% proportion of CF$_3$I in mixed gases, that is the most likely to be feasible.

As environmentally friendly insulation gas, CF$_3$I and its gas mixtures is a hot-topic on the global scope for gas insulating systems. The application of CF$_3$I and its gas mixtures in high-voltage apparatus not only meets the requirements and current trends on environmental protection in the international community, but also is a new direction in the field of electrical insulation.

To sum up, taking into account environmental characteristics, insulating properties and liquefaction temperature, CF$_3$I gas mixtures can be applied prior to C-GIS in the middle, low voltage system as well as GIL, GIT and other electrical devices in high-voltage system.

3. Power-frequency breakdown voltage of C$_3$F$_7$CN/CO$_2$ gas mixtures increases with the increase of mixing ratio from 0 to 10%. The relative dielectric strength of the gas mixtures showed a trend of saturated growth with the increase of mixing ratio, and power-frequency
breakdown voltage of $\text{C}_\text{F}_\text{3}$,$\text{CN}$/CO$_\text{2}$ gas mixtures when $\text{C}_\text{F}_\text{3}$,$\text{CN}$ is 8% ratio can reach 75% of that of pure SF$_\text{6}$ under the same condition. $\text{C}_\text{F}_\text{3}$,$\text{CN}$/CO$_\text{2}$ gas mixtures have potential of application of substitute for SF$_\text{6}$ in the electric power equipment, and the insulation of the other characteristics need further study. A deep insight into the partial discharge properties and corona stabilisation behaviour under strong inhomogeneous fields is needed for a full understanding.

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Appendix

Figure A1. AC breakdown voltage of SF$_\text{6}$,$\text{N}_\text{2}$,CO$_\text{2}$ gas mixtures with different gas pressures.
Figure A2. Maximum electric strength of SF₆, N₂, CO₂ gas mixtures with different gas pressures.

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