

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



---

# Development Prospect of Gas Insulation Based on Environmental Protection

---

Dengming Xiao

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.77035>

---

## 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 ( $\text{SF}_6$ ). The insulation characteristics of different components gas mixtures with 90% of nitrogen ( $\text{N}_2$ ) and carbon dioxide ( $\text{CO}_2$ ) as buffer gas and 10% octafluorocyclobutane ( $\text{c-C}_4\text{F}_8$ ), Trifluoroiodomethane ( $\text{CF}_3\text{I}$ ) and heptafluorobutyronitrile ( $\text{C}_4\text{F}_7\text{N}$ ) 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  $\text{c-C}_4\text{F}_8$ ,  $\text{CF}_3\text{I}$  and  $\text{C}_4\text{F}_7\text{N}$  (some friendly gases, which have the potential to replace  $\text{SF}_6$ ) are conducted trying to points out the further research direction.

**Keywords:** electrical equipment insulation, environmentally friendly gases, alternatives gases,  $\text{SF}_6$

---

## 1. Introduction

Because of its good electrical insulating properties, sulphur hexafluoride ( $\text{SF}_6$ ) can satisfy the insulating demands of the electrical apparatus.  $\text{SF}_6$  is nontoxic and non-combustible, which guarantees the security of its application in the gas insulating apparatus. What is more, the chemical properties of  $\text{SF}_6$  are stable and it can be compatible with most metal and solid insulating materials. There is little decomposing by-products after discharge or arc, which guarantees the following insulating function and protects apparatus. Nowadays,  $\text{SF}_6$  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 SF<sub>6</sub> 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. SF<sub>6</sub> is a strong greenhouse gas that will cause serious harm to the environment. The Global Warming Potential GWP of SF<sub>6</sub> is 23,900 times stronger than that of CO<sub>2</sub> [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 SF<sub>6</sub> 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], SF<sub>6</sub> was regarded as one of the six-kinds of greenhouse gas (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, PFC, HFC and SF<sub>6</sub>) 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 SF<sub>6</sub> in industry will be limited more and more [4, 5, 7]. Therefore, researching new method of gas insulating to replace SF<sub>6</sub> becomes an urgent work.

It is important to look for environmentally insulating gas with similar insulating characteristics and physicochemical properties of SF<sub>6</sub> to replace SF<sub>6</sub>. SF<sub>6</sub> 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 SF<sub>6</sub>, 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 SF<sub>6</sub> 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 SF<sub>6</sub>, 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-C<sub>4</sub>F<sub>8</sub>) are close to SF<sub>6</sub>, its cost is low and Greenhouse Warming Potential (GWP) is lower than SF<sub>6</sub>, the report has specially indicated that c-C<sub>4</sub>F<sub>8</sub> and its mixture can be the study subject for long time [10], so that researchers are focused on the study of this gas.

Gas	Relative breakdown voltage	Remarks
SF <sub>6</sub>	1	As reference of gas Relative breakdown voltage is 1
C <sub>3</sub> F <sub>8</sub>	0.90	With strong absorption to free electron, especially low-power free electron
c-C <sub>4</sub> F <sub>8</sub>	About 1.35	
2-C <sub>4</sub> F <sub>8</sub>	About 1.75	
1,3-C <sub>4</sub> F <sub>6</sub>	About 1.50	
Hexafluorobutadiene (2-C <sub>4</sub> F <sub>6</sub> )	About 2.3	
CHF <sub>3</sub>	0.27	With weaker absorption to free electron
CF <sub>4</sub>	0.39	

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

Besides c-C<sub>4</sub>F<sub>8</sub>, organic halogenated gas, trifluoroiodomethane (CF<sub>3</sub>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<sub>4</sub>F<sub>7</sub>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<sub>5</sub>F<sub>10</sub>O) and Undecafluorohexanoyl Fluoride (C<sub>6</sub>F<sub>12</sub>O). Properties of some potential alternative gases to SF<sub>6</sub> are shown in **Table 2**.

Gas	Physicochemical properties		Environmental characteristics	Electrical characteristics	
	Toxicity	Boiling point (unit: °C)	Relative GWP	Relative insulation characteristics [15]	Relative rising rate of recovery voltage (RRRV) characteristics
SF <sub>6</sub>	Nontoxic	-64	1	1.00	1.00
CF <sub>3</sub> I	Low-toxicity	-22.5	≈0	1.20	0.90
c-C <sub>4</sub> F <sub>8</sub>	Nontoxic	-6	0.3	1.30	—
g <sup>3</sup> (C <sub>4</sub> F <sub>7</sub> N/CO <sub>2</sub> )	Low-toxicity	24 (Pure)	0.02	0.85-1	—
C <sub>5</sub> F <sub>10</sub> O/air	Nontoxic	26.9 (Pure)	≈0	0.75-0.85	—
Hexafluoropropylene (C <sub>3</sub> F <sub>6</sub> )	Toxic	-29.6	≈0	1.01	—
Fluorinated 1,3-butadiene (C <sub>4</sub> F <sub>6</sub> )	Toxic	6-7	≈0	1.4	—
Fluorinated 2-butyne (C <sub>4</sub> F <sub>6</sub> )	Toxic	-25	≈0	1.7	—
Fluorinated 2-butene (C <sub>4</sub> F <sub>8</sub> )	Toxic	1.2	—	1.8	—

**Table 2.** Properties of potential alternative gas to sulphur hexafluoride (SF<sub>6</sub>) [8, 13, 14].

## 2. Analysis of potential alternative gas

### 2.1. Octafluorocyclobutane (c-C<sub>4</sub>F<sub>8</sub>)

Octafluorocyclobutane, c-C<sub>4</sub>F<sub>8</sub> is an important industrial gas. Nowadays, it is used in plasma etching technology or as refrigerant [16]. Similar to SF<sub>6</sub> gas, the performance to absorb electron easily of fluorine in c-C<sub>4</sub>F<sub>8</sub> is shown in the characteristics of the whole molecule, so that c-C<sub>4</sub>F<sub>8</sub> has a stronger absorption to free electron. c-C<sub>4</sub>F<sub>8</sub> is colourless, odourless, nontoxic to human bodies at low concentration, non-combustible, nonexplosive and with GWP of about 8700 relative to CO<sub>2</sub>. Though it belongs to greenhouse, but in the same conditions, its negative effects are just one third of SF<sub>6</sub> [17]. In addition, as organic halogenated gas, c-C<sub>4</sub>F<sub>8</sub> does not contain chlorine or bromine, so it is not harmful to the ozone layer. The molecule of c-C<sub>4</sub>F<sub>8</sub> 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<sub>4</sub>F<sub>8</sub> 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<sub>4</sub>F<sub>8</sub> and the rise of production. Nowadays, the price of c-C<sub>4</sub>F<sub>8</sub> is only a little bit higher than that of SF<sub>6</sub>, but if c-C<sub>4</sub>F<sub>8</sub> 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<sub>4</sub>F<sub>8</sub> and indicated that it had the feasibility to replace SF<sub>6</sub> 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<sub>4</sub>F<sub>8</sub>. 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<sub>4</sub>F<sub>8</sub>. The results of researches have shown that the insulation characteristics of pure c-C<sub>4</sub>F<sub>8</sub> are better than SF<sub>6</sub> in air pressure at 0.3 MPa and over. The breakdown voltage of the gas mixtures of c-C<sub>4</sub>F<sub>8</sub> and N<sub>2</sub> or CO<sub>2</sub> is higher than the gas mixtures of SF<sub>6</sub> with the same contents, and in low air pressure or atmospheric pressure, the breakdown voltage of the gas mixtures of c-C<sub>4</sub>F<sub>8</sub> can approach the gas mixtures of SF<sub>6</sub> with the same contents. In conclusion, c-C<sub>4</sub>F<sub>8</sub> and its gas mixtures have similar insulation characteristics with SF<sub>6</sub>, 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<sub>4</sub>F<sub>8</sub> is 200, higher than that of SF<sub>6</sub> (146.06), and it means that the condensing temperature of c-C<sub>4</sub>F<sub>8</sub> will be high, is about -6°C, higher than -63.6°C of SF<sub>6</sub>. 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<sub>2</sub>) or carbon dioxide (CO<sub>2</sub>), 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<sub>4</sub>F<sub>8</sub>.

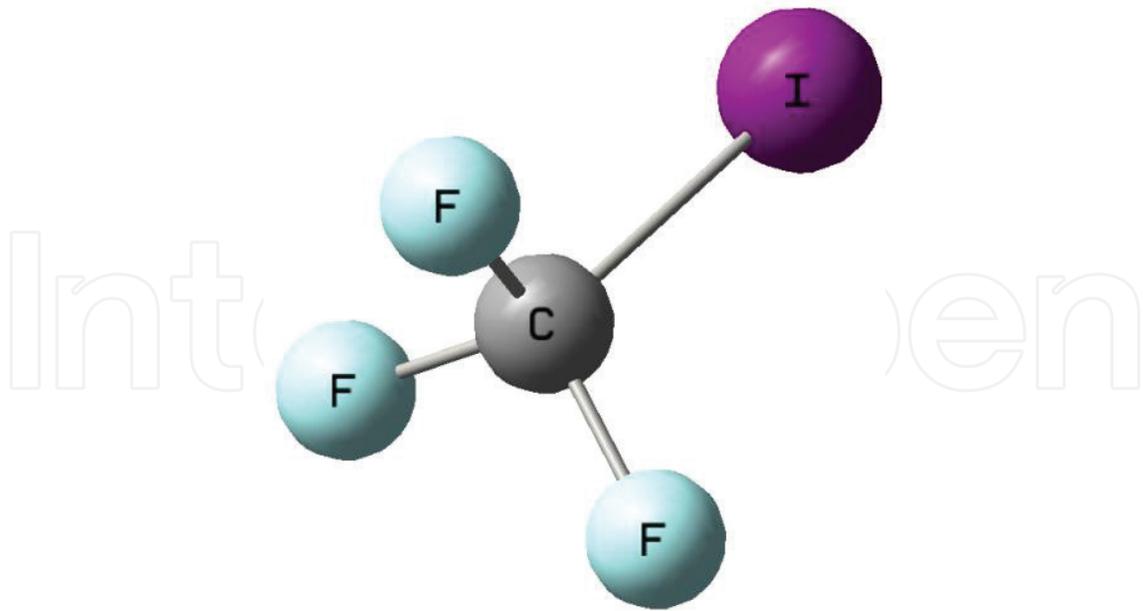
gas mixtures. Therefore,  $c\text{-C}_4\text{F}_8$  is not suited to be applied in apparatus as pure gas, or it cannot satisfy the demand of arctic alpine regions. Thus, it should be mixed with other gas in some ratios to reduce the condensing temperature of the gas mixtures and be used as gas mixtures.

## 2.2. Trifluoroiodomethane ( $\text{CF}_3\text{I}$ )

Trifluoroiodomethane ( $\text{CF}_3\text{I}$ ) is colourless, odourless, non-combustible and nonexplosive.  $\text{CF}_3\text{I}$  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  $\text{CO}_2$  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  $\text{CF}_3\text{I}$  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  $\text{CF}_3\text{I}$  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  $\text{CF}_3\text{I}$  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  $\text{CF}_3\text{I}$  and  $\text{SF}_6$ , as well as  $c\text{-C}_4\text{F}_8$ , 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  $\text{CF}_3\text{I}$  is a new industrial gas, its application in China is not widely extended, the production in China is low. Currently,  $\text{CF}_3\text{I}$  produced in China costs about 2000 RMB/kg, the price is much higher than  $\text{SF}_6$  [1]. The main reason why the price of  $\text{CF}_3\text{I}$  in China is higher than that for  $\text{SF}_6$  [1] is that the demand is very low. According to the producers of  $\text{CF}_3\text{I}$  (Beijing Yuji Science & Technology Co., Ltd.), after  $\text{CF}_3\text{I}$  will be used widely and will be mass-produced, the constant cost of  $\text{CF}_3\text{I}$  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  $c\text{-C}_4\text{F}_8$ .

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



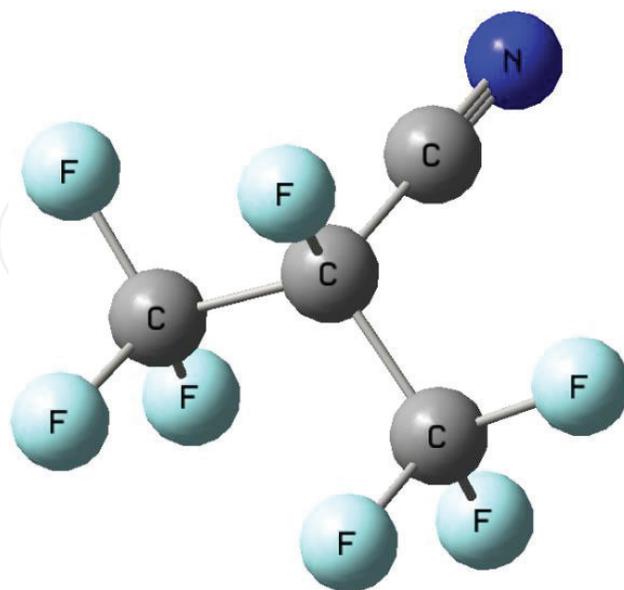
**Figure 1.** Molecule structure of  $\text{CF}_3\text{I}$ .

coefficient, attachment coefficient and electron drift velocity during the process of discharge of  $\text{CF}_3\text{I}$  and its gas mixtures with  $\text{N}_2$ ,  $\text{SF}_6$  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  $\text{CF}_3\text{I}$  by testing [25, 26]. They make the breakdown test to  $\text{CF}_3\text{I}$  and its gas mixtures with  $\text{N}_2$ ,  $\text{CO}_2$  and air by using lighting impulse. The results show that the insulation strength of pure  $\text{CF}_3\text{I}$  is better than that in  $\text{SF}_6$ , about 1.2 times than  $\text{SF}_6$ , and  $\text{CF}_3\text{I}-\text{CO}_2$  gas mixtures with high content also has better insulation characteristics to be able to replace  $\text{SF}_6$ . Many universities and academies in Europe also research the gas mixtures of  $\text{CF}_3\text{I}-\text{CO}_2$  and  $\text{CF}_3\text{I}-\text{N}_2$  in different conditions [24]. The results show that the positive synergistic effect of the gas mixtures of  $\text{CF}_3\text{I}$  and  $\text{N}_2$  is less obvious than that of the gas mixtures of  $\text{SF}_6$  and  $\text{N}_2$ , which means that in the same mixture ratio, the insulation strength of the gas mixtures of  $\text{CF}_3\text{I}-\text{CO}_2$  cannot increase with the rising content of  $\text{CF}_3\text{I}$  because of the synergistic effect [22]. In addition, the gas mixtures of  $\text{CF}_3\text{I}$  and  $\text{CO}_2$  with low content show better positive synergistic effect. Shanghai Jiao Tong University, Xi'an Jiao Tong University and Chongqing University in China has researched  $\text{CF}_3\text{I}$  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  $\text{CF}_3\text{I}$  and  $\text{N}_2$ ,  $\text{CO}_2$ , 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  $\text{CF}_3\text{I}$  [31, 32]. The results show that  $\text{CF}_3\text{I}$  has good electrical insulation characteristics, but the positive synergistic effect of the mixture of  $\text{CF}_3\text{I}$  and normal buffering gas is not obvious, so that the

insulation characteristics of its gas mixtures are lower than  $\text{SF}_6$ . Therefore, the research about the synergistic effect of  $\text{CF}_3\text{I}$  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  $\text{SF}_6$  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  $\text{C}_4\text{F}_7\text{N}$ , 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  $\text{C}_4\text{F}_7\text{N}$  have very good insulation performance, which can reach about two-times of that of  $\text{SF}_6$ . 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  $\text{C}_4\text{F}_7\text{N}$  is 195, with a high condensing temperature of  $-4.7^\circ\text{C}$ , so that it cannot replace  $\text{SF}_6$  as a single gas, it should become gas mixtures with buffering gas such as  $\text{N}_2$  or  $\text{CO}_2$ . 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  $\text{CO}_2$  is about 90% of the  $\text{SF}_6$  mixtures with the same amount of  $\text{CO}_2$ , 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.



**Figure 2.** Molecule structure of  $\text{C}_4\text{F}_7\text{N}$ .

The gas with the chemical formula of  $C_4F_7N$  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  $SF_6$  [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 ( $C=O$ ) such as  $C_5F_{10}O$  and  $C_6F_{12}O$ . 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-oxygen 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  $C_5F_{10}O$  and  $C_6F_{12}O$  are about two-times higher than  $SF_6$  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  $C_5F_{10}O$  with 266 and  $C_6F_{12}O$  with 316. Besides, the condensing temperature of  $C_5F_{10}O$  and  $C_6F_{12}O$  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.

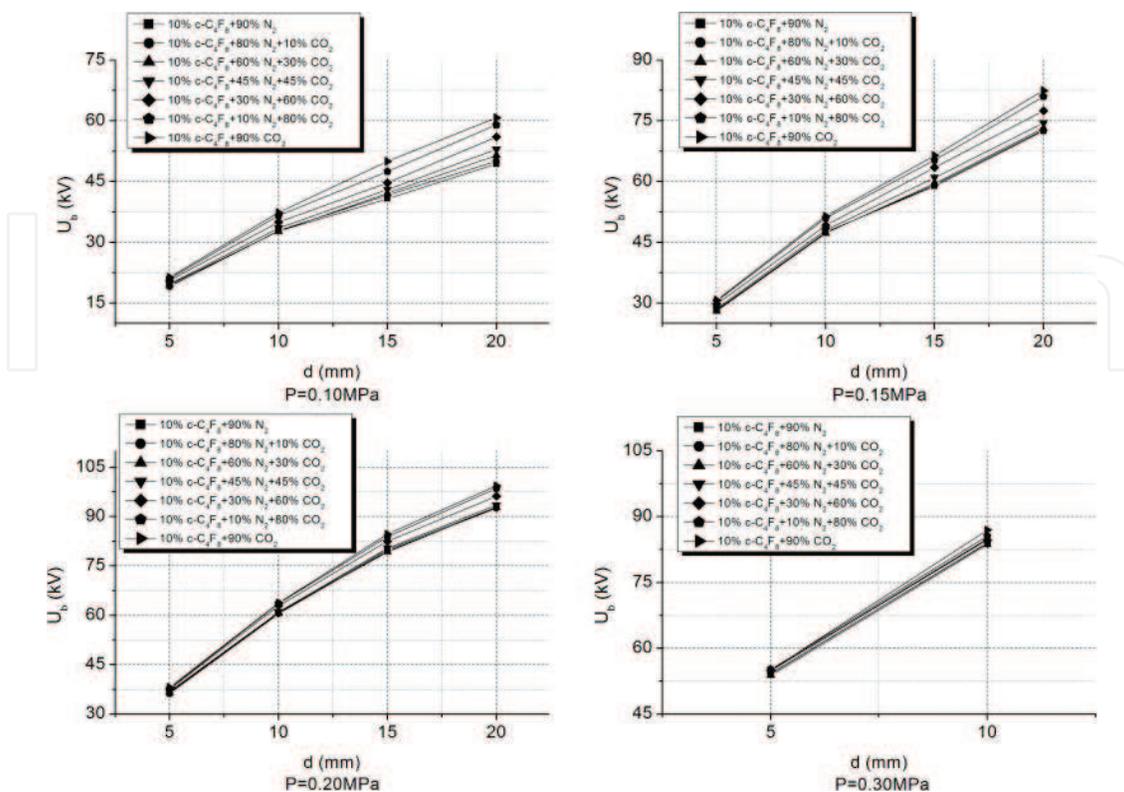
### 3. The power frequency AC breakdown characteristics of the c- $C_4F_8$ , $N_2$ , $CO_2$ gas mixtures

The breakdown voltage under AC voltage of the gas mixtures with a constant content of 10% of c- $C_4F_8$  and different content of  $N_2$  and  $CO_2$  has been measured by testing. **Figures 3 and 4** show the variety of the AC-breakdown voltage and maximum electric strength of the c- $C_4F_8$ ,  $N_2$ ,  $CO_2$  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  $c\text{-C}_4\text{F}_8$  mixtures is similar to the  $\text{SF}_6$  gas mixtures, the AC-breakdown voltage of the  $c\text{-C}_4\text{F}_8$ ,  $\text{N}_2$ ,  $\text{CO}_2$  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 has 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  $\text{SF}_6$ ,  $\text{N}_2$  and  $\text{CO}_2$  in Appendix **Figures A1** and **A2**.

**Figure 5** shows that under different gap distances, the variety of the AC-breakdown voltage of the  $c\text{-C}_4\text{F}_8$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures as the gas pressure changes. The AC-breakdown voltage of  $c\text{-C}_4\text{F}_8$  gas mixtures increases linearly as the air pressure increases without hump effect, and this trend is the same to  $\text{SF}_6$  gas mixtures. From **Figures 3–5**, we can see that the variety of the breakdown voltage of the  $c\text{-C}_4\text{F}_8$  gas mixtures with the same content as the air pressure and the electrodes gap changes is the same to  $\text{SF}_6$  gas mixtures. However, the curves of breakdown voltage of  $c\text{-C}_4\text{F}_8$  gas mixtures with different contents in the graphs are more concentrated than  $\text{SF}_6$ . 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  $c\text{-C}_4\text{F}_8$  and  $\text{CO}_2$  is the highest and the gas mixtures with  $\text{N}_2$  is lower, this is different from the properties of  $\text{SF}_6$  gas mixtures. When the gap distance is 20 mm, the AC-breakdown voltage of 10% $c\text{-C}_4\text{F}_8$ +90% $\text{CO}_2$  is about 10% higher than that of 10% $c\text{-C}_4\text{F}_8$ +90% $\text{N}_2$ .



**Figure 3.** AC-breakdown voltage of  $c\text{-C}_4\text{F}_8$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures with different gas pressures.

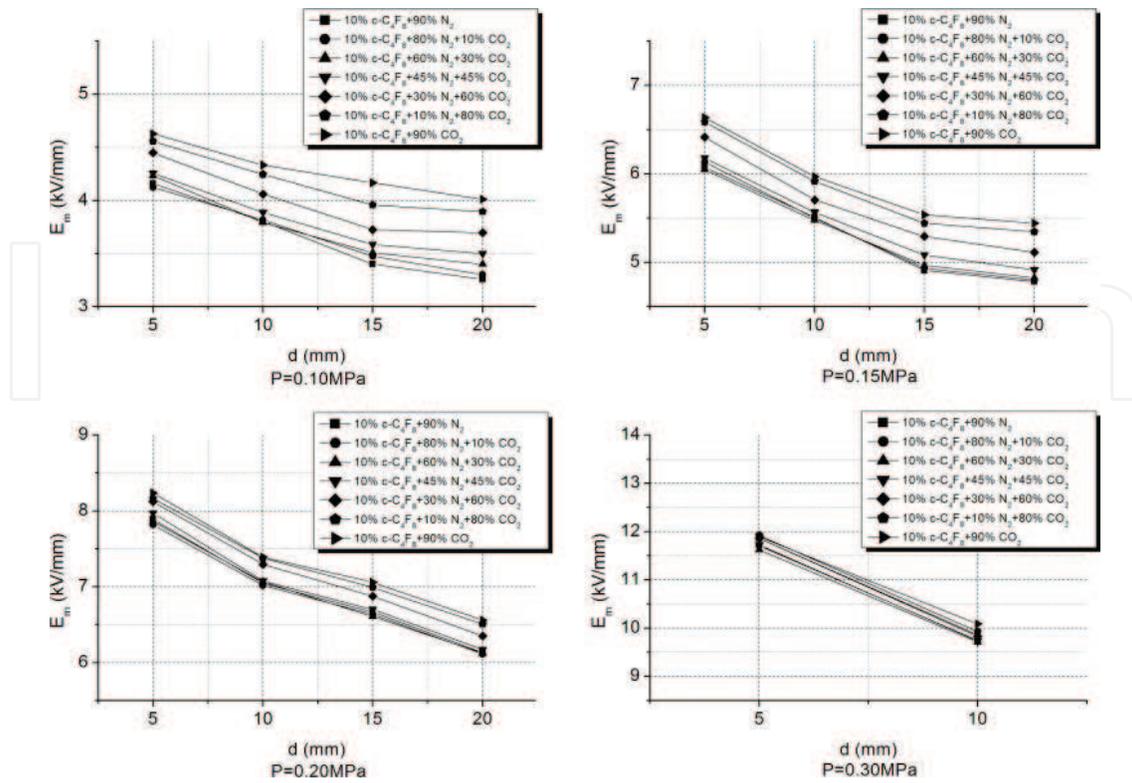


Figure 4. Maximum electric strength of  $c-C_4F_8$ ,  $N_2$ ,  $CO_2$  gas mixtures with different gas pressures.

Number	$c-C_4F_8/CF_3I$ mixing ratio (%)	$N_2$ mixing ratio (%)	$CO_2$ mixing ratio (%)
1	10	90	0
2	10	80	10
3	10	60	30
4	10	45	45
5	10	30	60
6	10	10	80
7	10	0	90

Table 3. Test gas mixtures for power frequency AC breakdown experiments.

Figure 6 shows under different gas pressures, the variety of the AC-breakdown voltage of the  $c-C_4F_8$ ,  $N_2$ ,  $CO_2$  gas mixtures as the content changes. If it is make the gas mixtures of  $10\%c-C_4F_8 + 90\%N_2$  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  $c-C_4F_8$  gas mixtures, the breakdown voltage of the triple gas mixtures in Figure 6 does not has an obvious increase

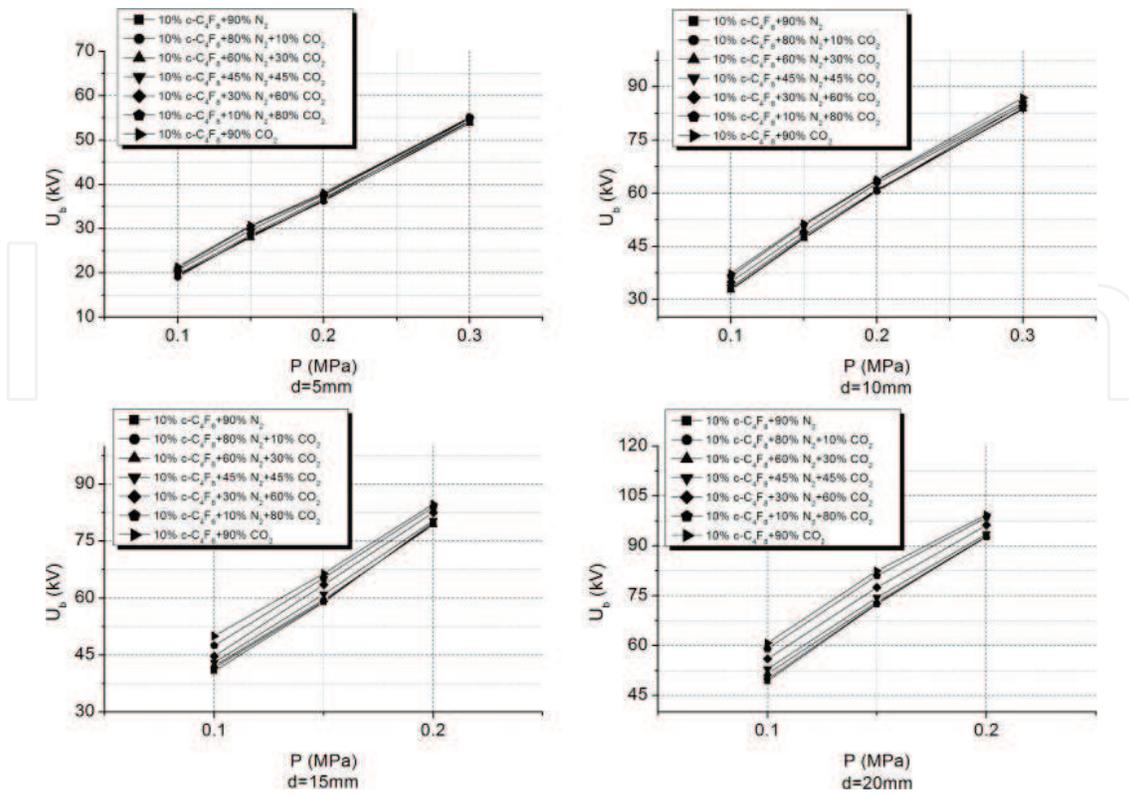


Figure 5. AC-breakdown voltage of c-C<sub>4</sub>F<sub>8</sub>, N<sub>2</sub>, CO<sub>2</sub> gas mixtures with different electrodes gap distances.

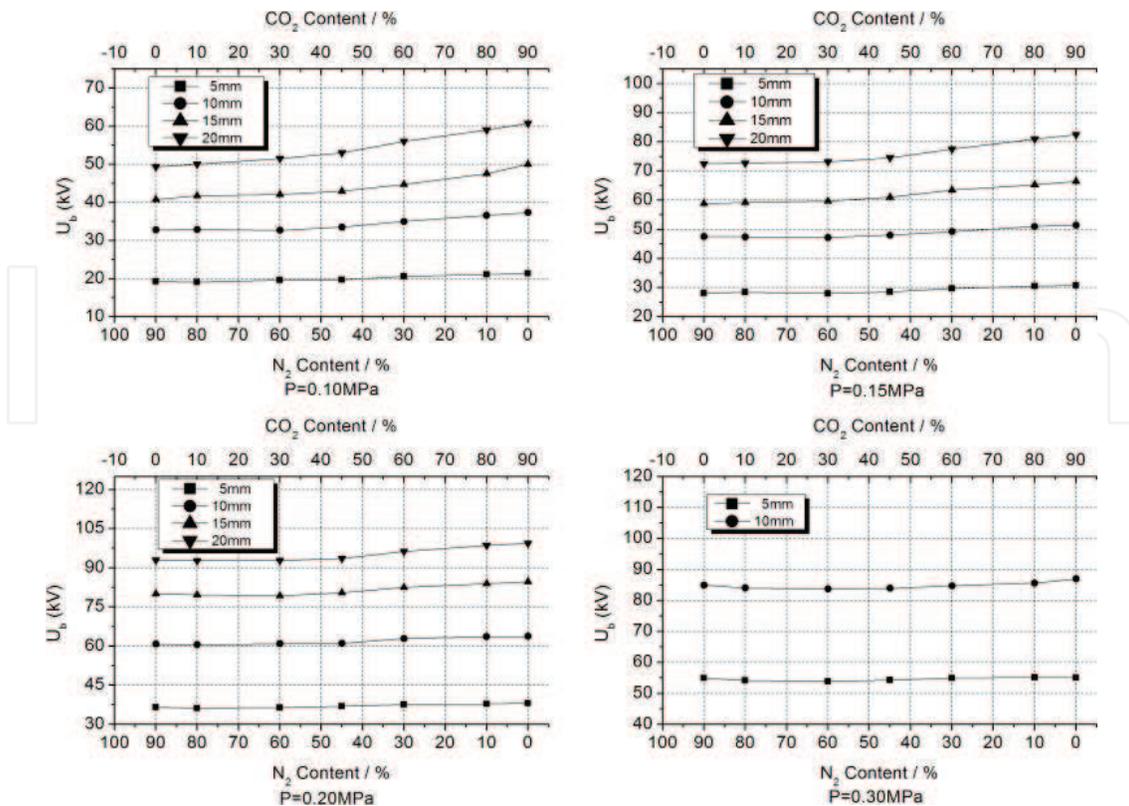


Figure 6. Relationship between AC-breakdown voltage and mixing contents of c-C<sub>4</sub>F<sub>8</sub>, N<sub>2</sub>, CO<sub>2</sub> gas mixtures.

immediately, and even it has a trend to reduce a little. Only after the content of  $N_2$  is lower than 30% and the content of  $CO_2$  is higher than 60%, the breakdown voltage can increase significantly.

#### 4. Power frequency AC-breakdown characteristics of the $CF_3I$ , $N_2$ , $CO_2$ gas mixtures

To  $CF_3I$ , it has been measured the breakdown characteristics for a constant content of 10%  $CF_3I$  and with different concentrations of  $N_2$  and  $CO_2$  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  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures as the gap changes. From Figure 7, it can be seen that the breakdown voltage of  $CF_3I$  gas mixtures gets higher as the electrodes gap gets bigger, but curves of different gas mixtures are more approached even closer compared with  $SF_6$  and  $c-C_4F_8$ . The breakdown voltage of  $CF_3I$  gas mixtures has little difference with different contents of  $N_2$  and  $CO_2$ . Moreover,  $N_2$ , which has better insulation strength, does not perform better than  $CO_2$  when it is mixed with  $CF_3I$ . In Figure 8, the maximum electric strength of  $CF_3I$  gas mixtures has a trend to reduce as the electrodes gap increases, but the curves are smoother than  $c-C_4F_8$ , which shows that the sensitivity to the electric non-uniformity of  $CF_3I$  is lower than  $c-C_4F_8$ .

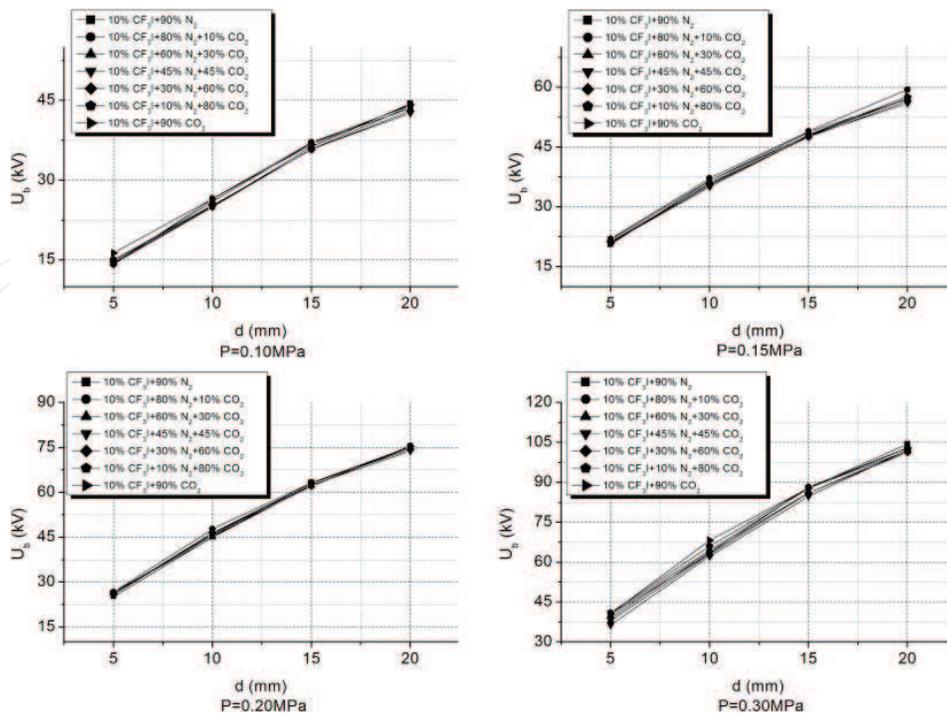


Figure 7. AC-breakdown voltage of  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures with different gas pressures.

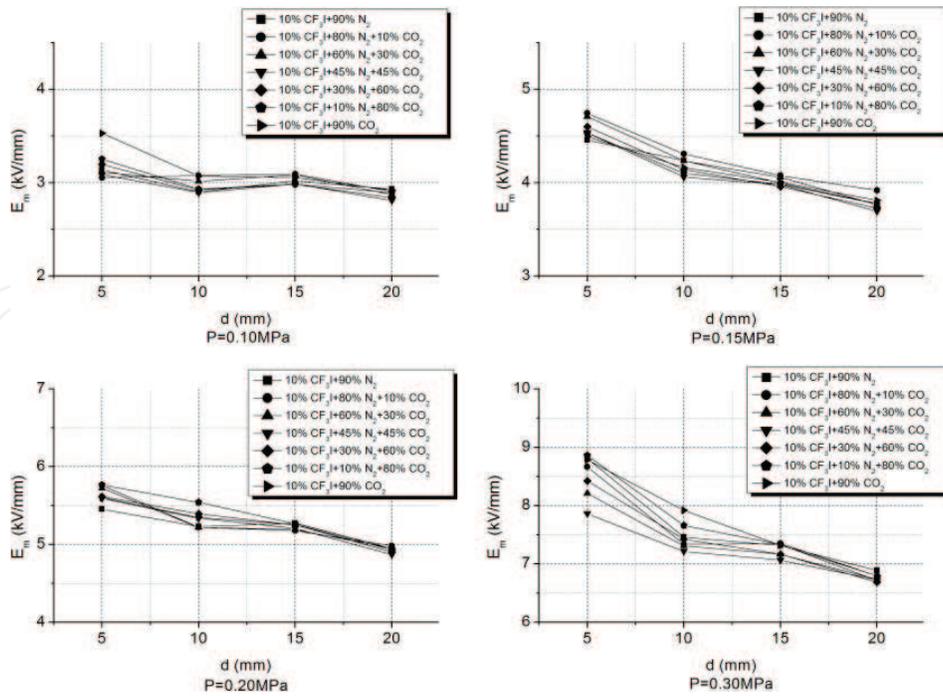


Figure 8. Maximum electric strength of  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures with different gas pressures.

Figure 9 shows, under different gaps of electrode, the variety of the AC-breakdown voltage for  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures as the gas pressure changes. Similar to the gas mixtures of  $SF_6$  and  $c-C_4F_8$ , the AC-breakdown voltage increases linearly as the air pressure increases, and without

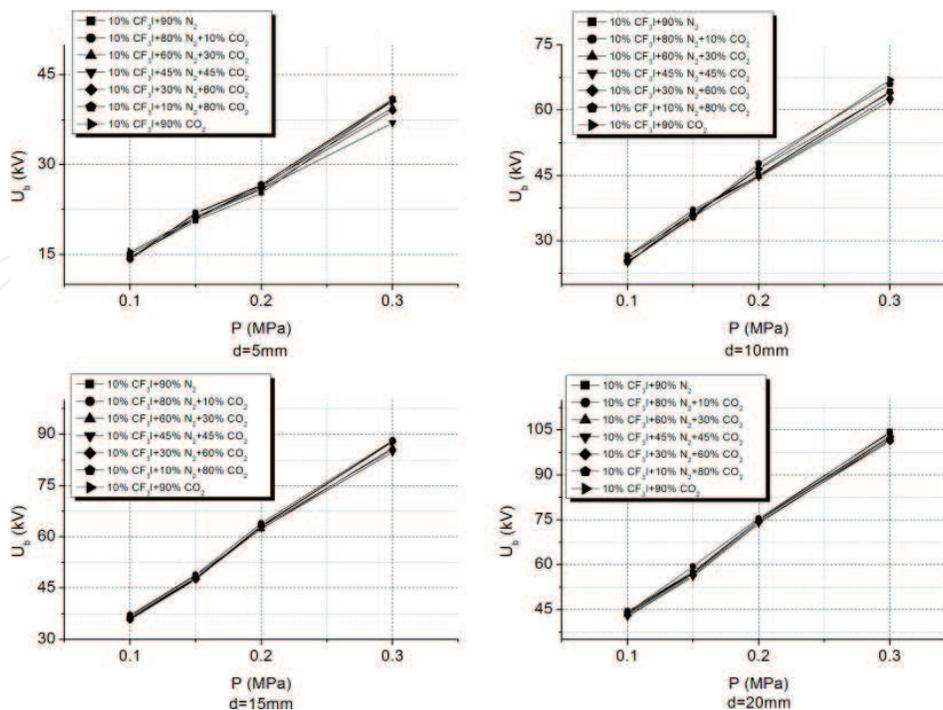


Figure 9. AC-breakdown voltage of  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures with different electrodes gap distances.

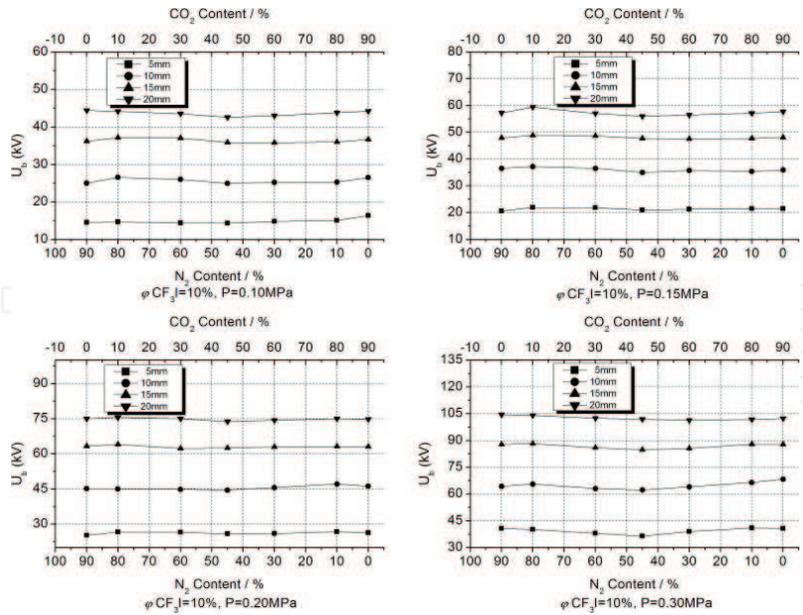


Figure 10. Relationship between AC-breakdown voltage and mixing contents of  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures.

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  $CF_3I$ ,  $N_2$ ,  $CO_2$  gas mixtures changes as the content changes. Generally, with the same mixing ratio of  $CF_3I$ , 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  $CF_3I$  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  $CF_3I$  gas mixtures.

### 5. Power frequency AC-breakdown characteristics of $C_3F_7CN/CO_2$

AC-breakdown characteristics of  $C_4F_7CN$  mixed with  $CO_2$  are tested for different concentrations. Figure 11 shows that AC-breakdown voltage of  $C_3F_7CN/CO_2$  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  $C_4F_7CN$   $k$  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  $C_3F_7CN/CO_2$  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  $C_3F_7CN$  increases to 20%, the insulation properties of  $C_3F_7CN/CO_2$  gas mixtures can approach that of pure  $SF_6$  under the same condition.

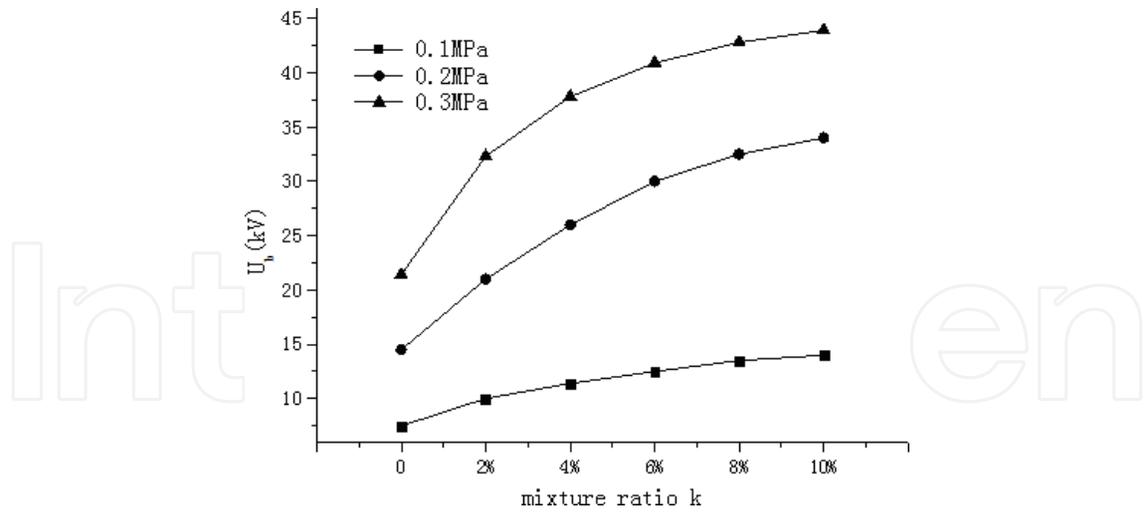


Figure 11. Relationship between power frequency breakdown voltage and mixture ratio of  $C_3F_7CN/CO_2$ .

## 6. Lightning impulse characteristics of $c-C_4F_8$ , $N_2$ , $CO_2$ gas mixtures

Figures 12 and 13 show the testing curves of the positive lightning impulse voltage of gas mixtures of 10%  $c-C_4F_8$  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,  $c-C_4F_8$  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

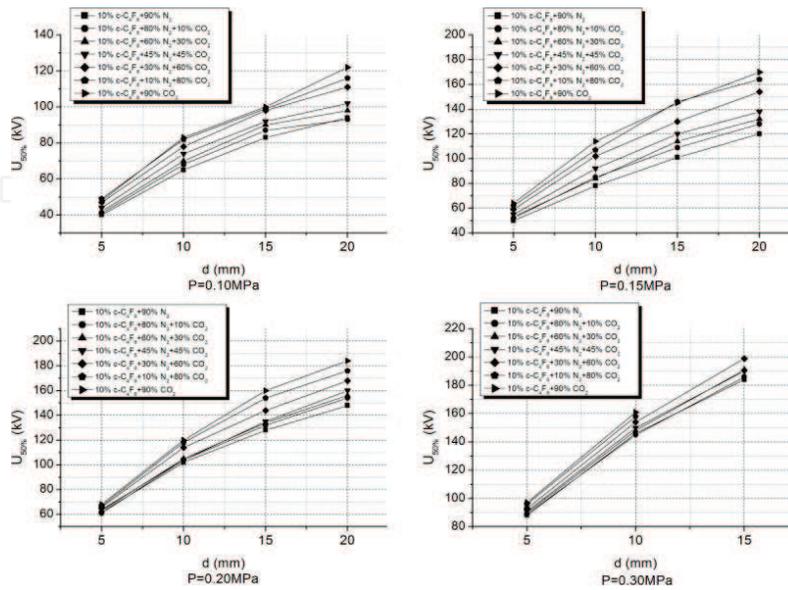


Figure 12. Positive lightning impulse breakdown voltage of  $c-C_4F_8$ ,  $N_2$ ,  $CO_2$  gas mixtures with different gas pressures.

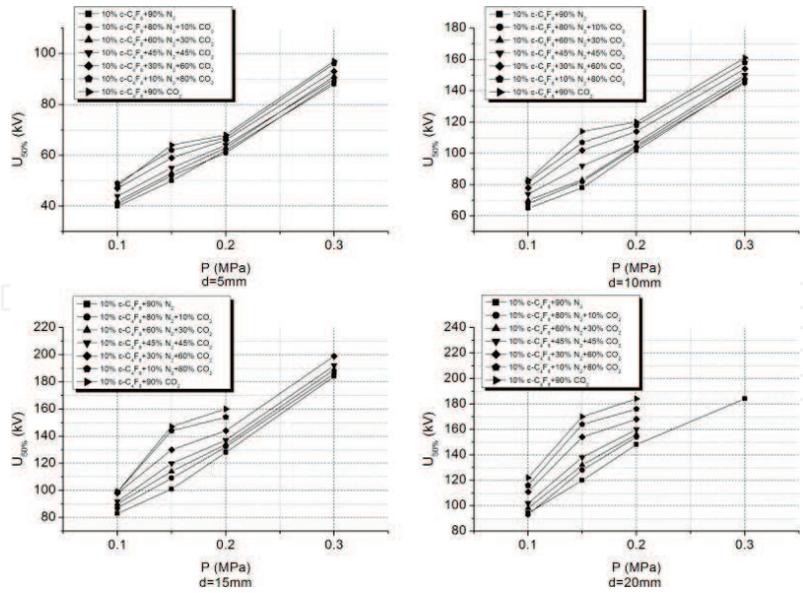


Figure 13. Positive lightning impulse breakdown voltage of  $c\text{-C}_4\text{F}_8$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures with different electrodes gap distances.

seen that  $10\%c\text{-C}_4\text{F}_8 + 90\%\text{CO}_2$  gas mixtures have the highest breakdown voltage and  $10\%c\text{-C}_4\text{F}_8 + 90\%\text{N}_2$  gas mixtures have the lowest breakdown voltage.

Figure 14 shows the different curves of positive lightning impulse breakdown voltage of the gas mixtures of  $10\%c\text{-C}_4\text{F}_8$  with  $\text{N}_2$  and  $\text{CO}_2$  as the content of  $\text{N}_2$  and  $\text{CO}_2$  changes. Because of  $\text{CO}_2$  itself has stronger ability to tolerate positive lightning impulse and it will not have obvious ionisation with  $c\text{-C}_4\text{F}_8$  compared with  $\text{N}_2$ , the breakdown voltage increases as the content

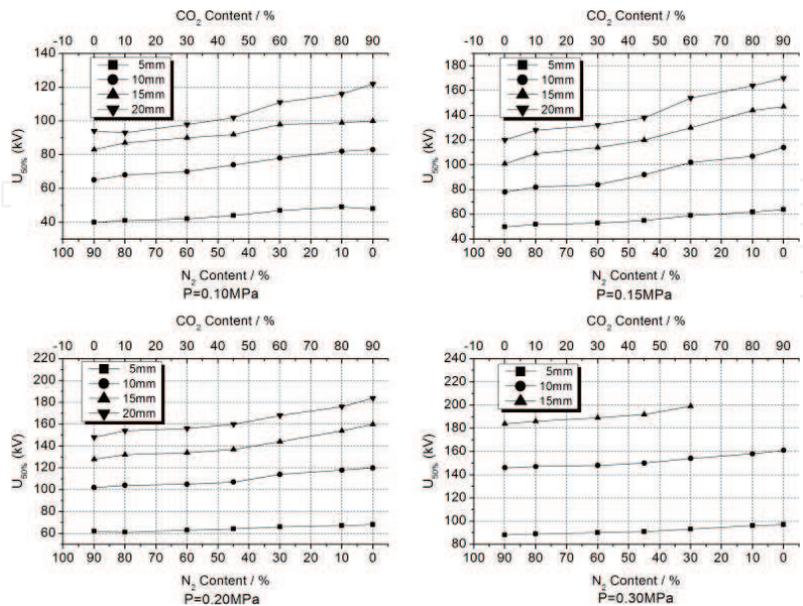


Figure 14. Relationship between positive lightning impulse breakdown voltage and mixing contents of  $c\text{-C}_4\text{F}_8$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures.

of  $\text{CO}_2$  in the gas mixtures increases. Because of the high resonance excitation, energy of  $\text{N}_2$  in the gas mixtures will have negative impact on  $\text{CO}_2$  when the content of  $\text{N}_2$  exceeds 30%. The increase of breakdown voltage of the gas mixtures is not obvious, and when the content of  $\text{N}_2$  is lower than 30%, the positive lightning impulse breakdown voltage shows more obvious trend to increase as the content of  $\text{CO}_2$  increases. Comparing 10% $\text{c-C}_4\text{F}_8$  + 90% $\text{N}_2$  and 10% $\text{c-C}_4\text{F}_8$  + 90% $\text{CO}_2$ , it is not hard to find that 10% $\text{c-C}_4\text{F}_8$  + 90% $\text{CO}_2$  has obviously higher positive lightning impulse breakdown voltage.

## 7. Lightning impulse characteristics of the $\text{CF}_3\text{I}$ , $\text{N}_2$ , $\text{CO}_2$ 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%  $\text{CF}_3\text{I}$  with  $\text{N}_2$  and  $\text{CO}_2$  of different contents. The positive lightning impulse voltage of  $\text{CF}_3\text{I}$  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  $\text{CF}_3\text{I}$  has the similar properties with  $\text{c-C}_4\text{F}_8$  and it is more appropriate to mix with  $\text{CO}_2$ .

Figure 17 shows the variation of the positive lightning impulse breakdown voltage of the gas mixtures consisting of 10%  $\text{CF}_3\text{I}$  and  $\text{N}_2$  as well as  $\text{CO}_2$  as the mixture ratio changes. The curves in Figure 17 have the same change with the  $\text{c-C}_4\text{F}_8$  gas mixtures, when the content of  $\text{N}_2$  is lower than 30%, the excitation energy can weaken the ionisation of  $\text{CF}_3\text{I}$  and  $\text{CO}_2$ , and the breakdown voltage of the gas mixtures increases obviously and this is the same with the changing trend of  $\text{c-C}_4\text{F}_8$  gas mixtures.

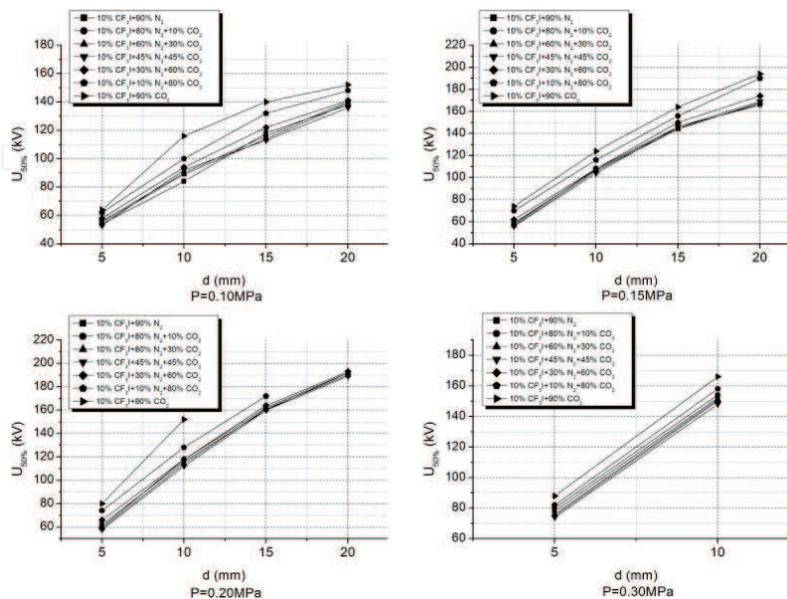


Figure 15. Positive lightning impulse breakdown voltage of  $\text{CF}_3\text{I}$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures with different gas pressures.

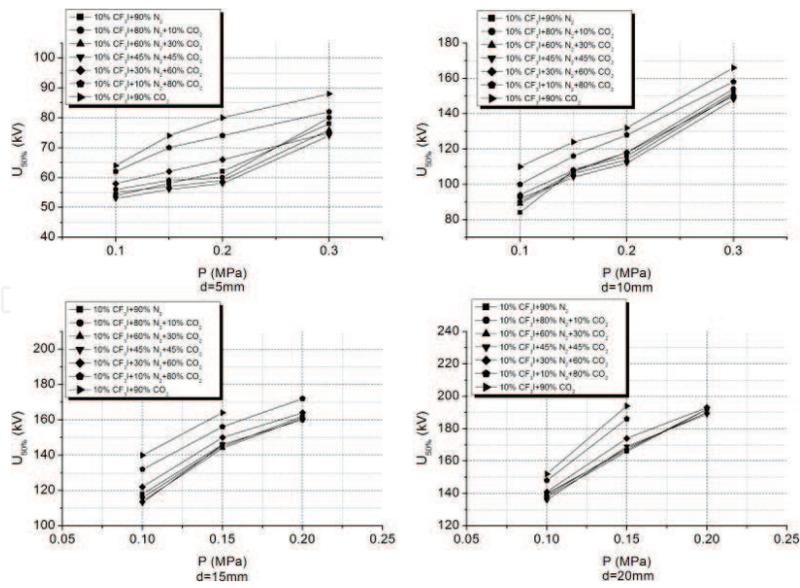


Figure 16. Positive lightning impulse breakdown voltage of  $\text{CF}_3\text{I}$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures with different electrodes gap distances.

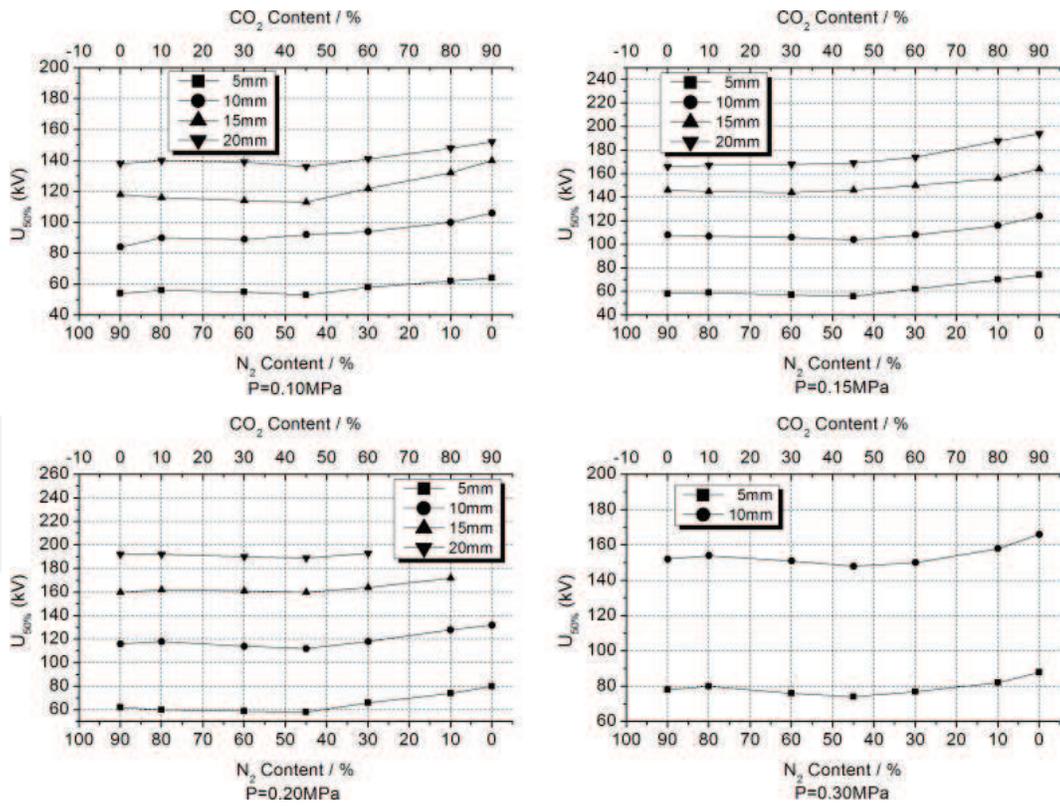


Figure 17. Relationship between positive lightning impulse breakdown voltage and mixing contents of  $\text{CF}_3\text{I}$ ,  $\text{N}_2$ ,  $\text{CO}_2$  gas mixtures.

## 8. Conclusion

1. In the consideration of insulation strength,  $c\text{-C}_4\text{F}_8$  gas mixtures with  $\text{N}_2$ ,  $\text{CO}_2$  is prior than current  $\text{SF}_6/\text{N}_2$  gas mixtures and pure  $\text{SF}_6$ . Moreover,  $c\text{-C}_4\text{F}_8$  gas mixtures can solve the problem of  $c\text{-C}_4\text{F}_8$  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,  $c\text{-C}_4\text{F}_8$  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  $\text{SF}_6$  and  $\text{SF}_6/\text{N}_2$  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  $c\text{-C}_4\text{F}_8$  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 analysis, under the same pressure conditions, the insulating strength of  $\text{CF}_3\text{I}$  is higher than that of  $\text{SF}_6$  while ensuring  $\text{CF}_3\text{I}$  not to be liquefied. Compared with compressed air or compressed  $\text{N}_2$  insulated in C-GIS,  $\text{CF}_3\text{I}$  can lower the pressure, in order to reduce the sealing technology and easy to manufacture. The shortcomings of high price also can be relieved after mixed with buffer gas. Therefore, using  $\text{CF}_3\text{I}$  as insulating gas in C-GIS has better comprehensive performance than that of the present C-GIS.

$\text{CF}_3\text{I}$  and  $\text{N}_2$  mixed gas can be used as replacement of  $\text{SF}_6$  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  $\text{CF}_3\text{I}$  in mixed gases, that is the most likely to be feasible.

As environmentally friendly insulation gas,  $\text{CF}_3\text{I}$  and its gas mixtures is a hot-topic on the global scope for gas insulating systems. The application of  $\text{CF}_3\text{I}$  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,  $\text{CF}_3\text{I}$  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  $\text{C}_3\text{F}_7\text{CN}/\text{CO}_2$  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  $C_3F_7CN/CO_2$  gas mixtures when  $C_3F_7CN$  is 8% ratio can reach 75% of that of pure  $SF_6$  under the same condition.  $C_3F_7CN/CO_2$  gas mixtures have potential of application of substitute for  $SF_6$  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.

### Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51337006).

### Appendix

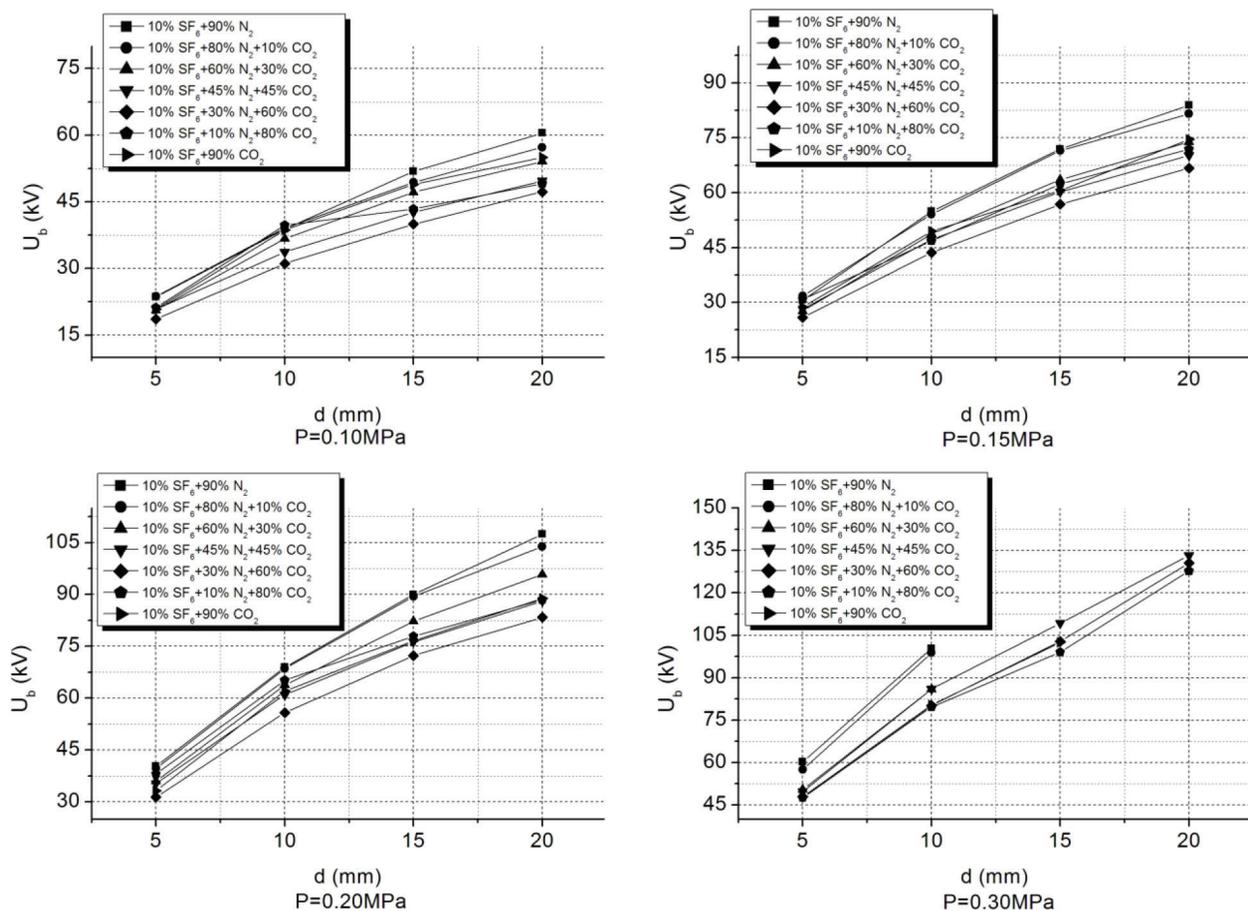


Figure A1. AC breakdown voltage of  $SF_6/N_2/CO_2$  gas mixtures with different gas pressures.

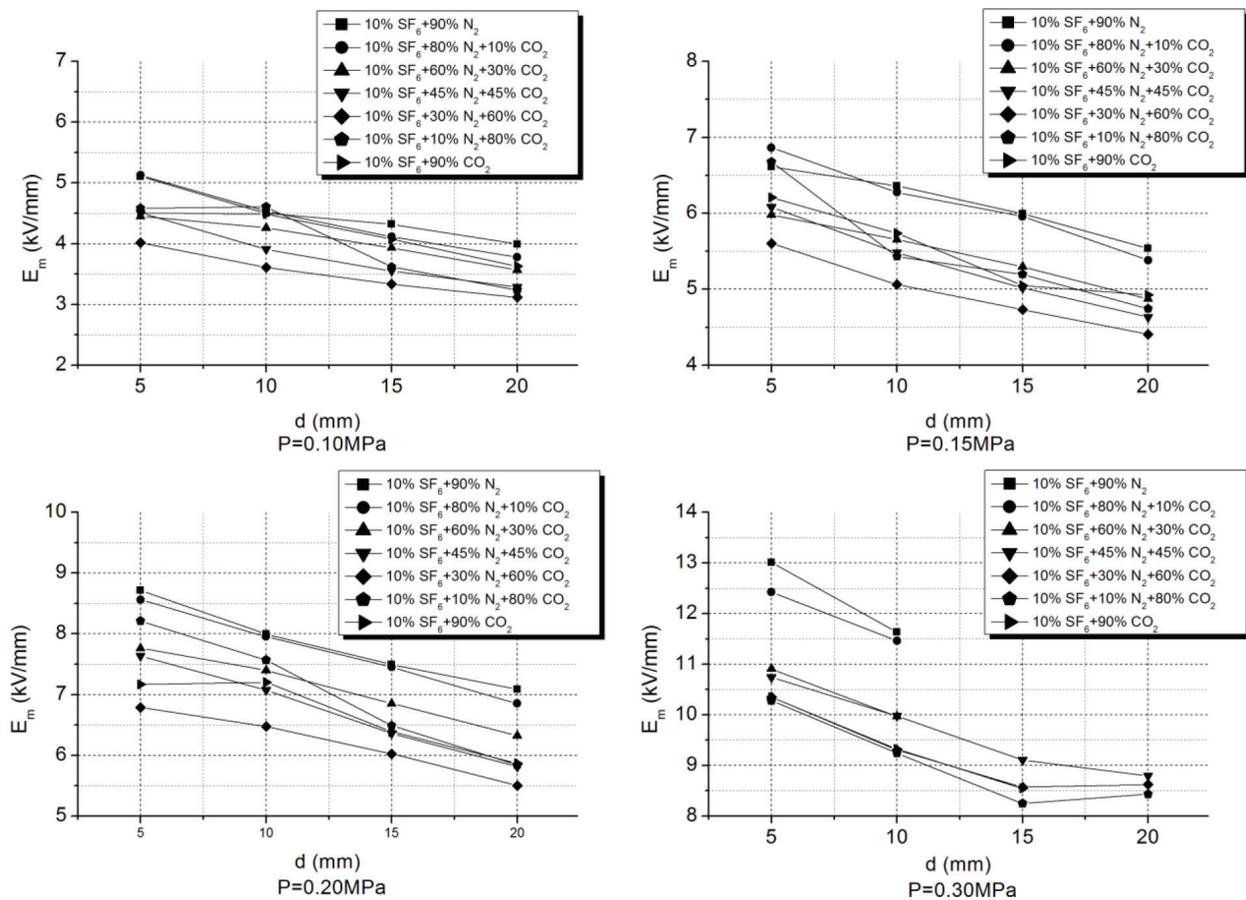


Figure A2. Maximum electric strength of SF<sub>6</sub>, N<sub>2</sub>, CO<sub>2</sub> gas mixtures with different gas pressures.

## Author details

Dengming Xiao

Address all correspondence to: [dmxiao@sjtu.edu.cn](mailto:dmxiao@sjtu.edu.cn)

Shanghai Jiao Tong University, Shanghai, China

## References

- [1] Yunkun D. Basic research of the environmentally friendly insulating gas CF<sub>3</sub>I for its application in electric power apparatus [PhD thesis]. Shanghai: Shanghai Jiao Tong University; 2016
- [2] Reilly J, Prinn R, Harnisch J, Fitzmaurice J, Jacoby H, Kicklighter D, et al. Multi-gas assessment of the Kyoto protocol. *Nature*. 1999;401:3466-3469

- [3] Qingchen C, Yongxiang Z, Gao X, Wang M. Paris agreement: A new start for global governance on climate. *Progress in Climate Change Research*. 2016;**12**:61-67
- [4] National Development and Reform Commission. *China's Policy and Action on Climate Change 2017*. Beijing: China Government; 2017
- [5] WMO. The state of greenhouse gases in the atmosphere based on global observations through 2016. *WMO Greenhouse Gas Bulletin (GHG Bulletin)*. October 2017;**13**, 30:1
- [6] CE. *Why Climate Policy-Makers can't Afford to Overlook Fully Fluorinated Compounds*. Washington: World Resources Institute; 1995
- [7] Xiangwan D. Opening a new stage of global green low-carbon development. *China Awards for Science and Technology*. 2016:6-6
- [8] Dengming Xiao. *Gas Discharge and Gas Insulation*. China: Springer; 2016
- [9] Wvvh W, Wwvl W, Connor JT, Astin AV, Engineerin SK. National Bureau of Standards. *IRE Transactions on Aeronautical & Navigational Electronics*. 2012;**2**:111-114
- [10] Liu X, Wang J, Wang Y, Zhang Z, Xiao D. Analysis of the insulation characteristics of c-C<sub>4</sub>F<sub>8</sub>/CO<sub>2</sub> gas mixtures by the Monte Carlo method. *Journal of Physics D: Applied Physics*. 2008;**41**:015206
- [11] Costello MG, Flynn RM, Bulinski MJ. Fluorinated nitriles as dielectric gases. *Google Patents*; 2013
- [12] Nishimura H, Huo WM, Ali MA, Kim YK. Electron-impact total ionization cross sections of CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, and C<sub>3</sub>F<sub>8</sub>. *Journal of Chemical Physics*. 1999;**110**:3811-3822
- [13] Devins J. Replacement gases for SF<sub>6</sub>. *IEEE Transactions on Electrical Insulation*. 1980: 81-86
- [14] Christophorou LG, Olthoff JK, Green DS. Gases for electrical insulation and arc interruption: Possible present and future alternatives to pure SF<sub>6</sub>. *NIST TN-1425*. 2011;**8**:391
- [15] Xiao D, Zhu L, Li X. Electron transport coefficients in SF<sub>6</sub> and xenon gas mixtures. *Journal of Physics D: Applied Physics*. 2000;**33**:L145
- [16] Christophorou LG, Olthoff JK. Electron interactions with c-C<sub>4</sub>F<sub>8</sub>. *Journal of Physical and Chemical Reference Data*. 2001;**30**:449-473
- [17] Zhao S, Jiao J, Zhao X, Zhang H, Xiao D, Yan JD. Synergistic effect of c-C<sub>4</sub>F<sub>8</sub>/N<sub>2</sub> gas mixtures in slightly non-uniform electric field under lightning impulse. In: *IEEE Electrical Insulation Conference*; 2016. pp. 531-534
- [18] Wu B-T, Xiao D-M, Liu Z-S, Zhang L-C, Liu X-L. Analysis of insulation characteristics of c-C<sub>4</sub>F<sub>8</sub> and N<sub>2</sub> gas mixtures by the Monte Carlo method. *Journal of Physics D: Applied Physics*. 2006;**39**:4204
- [19] Macko WMJ. Toxicity review for Iodotrifluoromethane (CF<sub>3</sub>I). In: *Halon Options Technical Working Conference*. US. 1999

- [20] NFP Association. Standard on Clean Agent Fire Extinguishing Systems. In: NFPA 2001. New Orleans, LA, U.S.: Technical Committee on Halon Alternative Protection Options; 2000. p. 109
- [21] De Urquijo J. Is  $\text{CF}_3\text{I}$  a good gaseous dielectric? A comparative swarm study of  $\text{CF}_3\text{I}$  and  $\text{SF}_6$ . *Journal of Physics: Conference Series* 86, 2007:012008
- [22] Yun-Kun D, Deng-Ming X. The effective ionization coefficients and electron drift velocities in gas mixtures of  $\text{CF}_3\text{I}$  with  $\text{N}_2$  and  $\text{CO}_2$  obtained from Boltzmann equation analysis. *Chinese Physics B*. 2013;**22**:035101
- [23] Kimura M, Nakamura Y. Electron swarm parameters in  $\text{CF}_3\text{I}$  and a set of electron collision cross sections for the  $\text{CF}_3\text{I}$  molecule. *Journal of Physics D: Applied Physics*. 2010;**43**:145202
- [24] Cressault Y, Connord V, Hingana H, Teulet P, Gleizes A. Transport properties of  $\text{CF}_3\text{I}$  thermal plasmas mixed with  $\text{CO}_2$ , air or  $\text{N}_2$  as an alternative to  $\text{SF}_6$  plasmas in high-voltage circuit breakers. *Journal of Physics D: Applied Physics*. 2011;**44**:495202
- [25] De Urquijo J, Mitrani A, Ruíz-Vargas G, Basurto E. Limiting field strength and electron swarm coefficients of the  $\text{CF}_3\text{I}$ - $\text{SF}_6$  gas mixture. *Journal of Physics D: Applied Physics*. 2011;**44**:342001
- [26] De Urquijo J, Juárez A, Basurto E, Hernández-Ávila J. Electron impact ionization and attachment, drift velocities and longitudinal diffusion in  $\text{CF}_3\text{I}$  and  $\text{CF}_3\text{I}$ - $\text{N}_2$  mixtures. *Journal of Physics D: Applied Physics*. 2007;**40**:2205
- [27] Xiaoxing Z, Junjie Z, Ju T, Song X, Yefei H. "Experimental research on the partial discharge insulation properties of  $\text{CF}_3\text{I}/\text{CO}_2$  and  $\text{CF}_3\text{I}/\text{N}_2$  gas mixtures," *Proceedings of the CSEE*, vol. 34, pp. 1948-1956, 2014
- [28] ZHAO Su, XIAO Dengming, ZHANG Hui, and DENG Yunkun, "Investigation on discharge polarity effect of  $\text{CF}_3\text{I}/\text{N}_2$  gas mixtures under lightning impulse," *Proceedings of the CSEE*, vol. 37, pp. 3636-3642, 2017
- [29] Li X, Zhao H, Wu J, Jia S. Analysis of the insulation characteristics of  $\text{CF}_3\text{I}$  mixtures with  $\text{CF}_4$ ,  $\text{CO}_2$ ,  $\text{N}_2$ ,  $\text{O}_2$  and air. *Journal of Physics D: Applied Physics*. 2013;**46**:345203
- [30] Zhao X, Li B, Xiao D, Deng Y. Breakdown characteristics of  $\text{CF}_3\text{I}$ - $\text{N}_2$  gas mixtures in a needle-plate geometry. *IEEE Transactions on Dielectrics and Electrical Insulation*. 24 April 2017;**24**:869-875
- [31] Xiao S, Cressault Y, Zhang X, Teulet P. The influence of Cu, Al, or Fe on the insulating capacity of  $\text{CF}_3\text{I}$ . *Physics of Plasmas*. 2016;**23**:123505
- [32] Kochetov I, Napartovich A, Vagin N, Yuryshv N. Mechanism of pulse discharge production of iodine atoms from  $\text{CF}_3\text{I}$  molecules for a chemical oxygen-iodine laser. *Journal of Physics D: Applied Physics*. 2009;**42**:055201
- [33] Kieffel Y. Characteristics of G3—An alternative to  $\text{SF}_6$ . In: *IEEE International Conference on Dielectrics*; 2016. pp. 880-884

- [34] Switzerland: ABB achieves breakthrough in switchgear technology with eco-efficient insulation gas. Tendersinfo News. 2014
- [35] Rabie M, Franck CM. Assessment of eco-friendly gases for electrical insulation to replace the most potent industrial greenhouse gas SF<sub>6</sub>. *Environmental Science & Technology*. 2017;369-380
- [36] Stoller PC, Doiron CB, Tehlar D, Simka P, Ranjan N. Mixtures of CO<sub>2</sub> and C<sub>5</sub>F<sub>10</sub>O perfluoroketone for high voltage applications. *IEEE Transactions on Dielectrics & Electrical Insulation*. 2017;24:2712-2721
- [37] Zhao S, Xiao D, Jiao J, Zhao X. Discharge characteristics of c-C<sub>4</sub>F<sub>8</sub>/N<sub>2</sub> with and without insulator under standard lightning impulse. Presented at the IEEE Electrical Insulation Conference; 2016