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Research of UHV Gas-insulated Transmission Line (GIL) with Perfluoronitrile (C_4F_7N) Gas

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SUMMARY

Sulfur hexafluoride (SF_6) gas has been extensively used in the electrical power equipment as an excellent insulation and arc-quenching medium. Nevertheless, with the increasing demand for environment protection, SF_6 is restricted to be used due to its strong greenhouse effect and it is urgent to research and develop the new environmentally-friendly gas to replace SF_6. Considering the actual needs of high voltage equipment and its application, C_4F_7N is discovered to be the most promising alternative gas due to its excellent dielectric strength but lower impact on global warming. It is of great significance to comprehensively research the physiochemical properties of C_4F_7N and the characteristics during its applications in high voltage equipment. Meanwhile, it is also significant for the development of environmental electrical equipment to sufficiently achieve the applications of C_4F_7N in engineering. As an important equipment for electric power transmission, GIL plays a vital role in the development of electrical power system, especially for the transmission with special geographical conditions during the construction of ultra-high voltage (UHV) engineering with long transmission distance. It is also a better choice for the development of SF_6 alternative technology because it has a large gas consumption. A 1000 kV UHV GIL prototype filling with C_4F_7N was developed, considering the strict environment protection and insulation requirements. Investigations of the key technologies for this prototype design, manufacturing and its operation have been carried out. In this paper, the molecular structure design of SF_6 substitute gas was firstly introduced. New alternative gases including C_4F_7N were designed by the constructed quantitative Structure-Activity Relationship (SAR) model, which describes the relationships of molecular structure respectively with insulation strength and liquefaction temperature of the gas itself. The methods of functional group substitution and molecular bond hybridization were innovated. On this basis, the synthesis of C_4F_7N gas with multiple routes in the laboratory was also studied with four scenarios proposed and the gas purity could reach 99.9% which is sufficient for its utilisation in the equipment. Furthermore, the insulation characteristics of C_4F_7N gas mixed with the buffer gases of CO_2, N_2 were experimentally studied. The control value of electrical field strength for insulation design was proposed. In addition, the compatibility of C_4F_7N/CO_2 gas mixture with the commonly used solid material was studied by proposing the gas-solid compatibility configuration for the design of 1000 kV prototype. From the study, the compatibility of C_4F_7N/CO_2 gas mixture with epoxy resin and rubber were obtained and it is also observed that the fluoro-rubber was more suitable as the sealing material. According to the above achievements, the design of supporting insulator when using C_4F_7N/CO_2 gas mixture as the filling medium was optimised as well as the prototype of the 1000 kV UHV environmental GIL. The prototype passed the required type test and carried out the live test in the UHV AC test base with good operation condition. To support the tests, gas filling and detection as well as the status monitoring were technically solved to ensure the reliability of the equipment.

KEYWORDS

UHV GIL; C_4F_7N; Structure-Activity Relationship (SAR) model; synthesis; gas-solid compatibility

1 INTRODUCTION

SF_6 gas is an excellent gaseous dielectric with strong insulating and arc-quenching properties, which has been extensively used in electric power grid, e.g., switchgears in power plants, electric transmission, and distribution equipment. The consumption of SF_6 in the power grid reaches more than 8,000 tons per year and the amount of SF_6 emitted into the atmosphere has also increased by 50% over the past decade. However, SF_6 has already been listed as a strong greenhouse gas in *the Kyoto Protocol*, of which its global warming potential (GWP) is 23,500 times higher than carbon dioxide (CO_2) and the persistence of its atmospheric lifetime is up to 3,200 years. Obviously, the environmental influences of using SF_6 cannot be ignored anymore and it is necessary to find out new environmentally-friendly gases to replace SF_6 and also improve the environmental benefits of the electric power equipment [1].

In recent years, C_4F_7N and $C_5F_{10}O$ are discovered as two potential alternative gases for substituting SF_6. From the view of liquefaction temperature and dielectric strength of the gas, C_4F_7N is perceived as a more optimized choice. Focuses on the feasibility of C_4F_7N replacement, it is necessary to research the electrical characteristics, physical and chemical properties, and also the compatibilities between C_4F_7N and common solid materials, etc. to support its engineering application in the power grid system. Among the existing electrical apparatus, UHV GIL is chosen as the research object where C_4F_7N is filled as the working medium. UHV GIL is the key equipment to solve the bottleneck of power transmission in areas with special geographical conditions, which also has large gas consumption (even 19 tons per kilometre). Research and development of 1000 kV environmentally-friendly GIL with C_4F_7N gas not only improves the development of UHV power grid, but also has demonstrative and leading impacts on the upgrade of environment protection of other gas-insulated equipment. So far, C_4F_7N has been already used in the electrical apparatus such as 145 kV gas-insulated switchgear (GIS), 245 kV current transform (CT) and 420 kV GIL with engineering demonstration while the voltage is limited to the extra high voltage (EHV) level and the key technologies of UHV environment protection GIL have not been systematically studied. In order to effectively promote the environmentally-friendly alternative technology, it is urgent to study the scientific and technical problems such as molecule design of environmental insulation gas, discharge characteristics of the gas, gas-solid compatibility for using in UHV GIL and multi-physics simulation for the GIL prototype design and manufacturing [2]-[4].

Relevant studies have been carried out to follow the mentioned problems above. In the field of gas molecular design and industrial preparation, Westinghouse and NIST tried to filtrate the existed gases from published references and patents to select which is better for engineering applications. It was found that no single gas could comprehensively outperform the SF_6. Companies of Alstom, 3M, GE and ABB have selected a series of environmentally-friendly insulation gases from the existed foamer, extinguishant and refrigerant including C_4F_7N, $C_5F_{10}O$ and $C_6F_{12}O$. As explained before, the liquefaction temperature of these gases is relatively higher compared with SF_6, especially $C_5F_{10}O$ and $C_6F_{12}O$ which their liquefaction temperatures are respectively 26.5 ℃ and 49.2 ℃. They must be mixed with the buffer gases to satisfy the engineering requirements. Besides that, theoretical research on the molecular design of the alternative gas has been carried out as well. Some parameters that describe the molecule properties such as molecular weight, ionization energy, polarizability and electronegativity can be experimentally measured. On this basis, the activities relationship model can be established to qualitatively predict the gas insulating property. From 2000s, the activities relationship model was improved with the calculation of parameters that describe the molecule properties following the Density Functional Theory (DFT), but only limited on the computation of the existed compounds [5]-[6].

Electric Power Research Institute (EPRI), GE, ABB, China Electric Power Research Institute (CEPRI), Xi'an Jiaotong University, Wuhan University and etc. also carried out the investigations in terms of the gas discharge characteristics, gas-solid compatibility and arc quenching performance of the gas such as C_4F_7N, $C_5F_{10}O$, CF_3I, c-C_4F_8 and their mixture with the buffer gas [7]-[8]. With the obtained characteristics of the gas, the prototype design and manufacturing of the GIL are also performed as well to achieve the engineering applications of the gas. For example, a test section of SF_6 insulated GIL with rated voltage of 1200 kV was produced~~ by AZZ company~~. A 420 kV GIL using C_4F_7N/CO_2 mixture was developed ~~by GE ~~and put into operation at ~~Sellindge ~~substation ~~in UK~~as well. ~~Pinggao Group, Xi'an XD and SGCC company developed ~~SF_6 1000 kV GIL test section and 1000 kV SF_6/N_2 GIL prototype were constructed, which indicates extensive experiences of the technical capabilities especially in the

UHV GIL development of UHV GIL [9]-[10]. However, it is still technically blank for the development of UHV environmental GIL in the world.

Focusing on the problematic situation, the research is hence scientifically carried out from gas molecular design and synthesis to the study of the insulation characteristics and compatibility of the gas, and finally complete the UHV GIL prototype design and manufacturing. In this paper, the molecular design of the new environmentally-friendly insulation gas including C_4F_7N is firstly introduced in section 2. Synthesis of C_4F_7N is secondly described in section 3 and then the experimental research of C_4F_7N and C_4F_7N/CO_2 gas mixture insulation and compatibility characteristics in section 4. Finally, the development of UHV environmental GIL associated with its operation and maintenance is presented in section 5.

2 MOLECULAR STRUCTUAL DESIGN OF ENVIRONMENTAL INSULATION GAS

Facing the challenges of insulation and liquefaction features of the environmental gas, the SAR model was established based on Quantum Mechanics (QM) to describe the relationship between gas molecular structure and its insulation characteristics as well as its liquefaction. Two approaches for gas structure design were respectively revealed: Functional group substitution and molecular bond hybridization. As the special discharge phenomenon for insulating gas mixture, the synergetic effect was also considered to determine a preferred gas configuration.

Actually, new environmentally-friendly gases for SF_6 replacement are mainly selected from polyfluorinated compounds and perfluorinated compounds. Nevertheless, traditional methods such as Configuration Interaction with Single, Double and Triple Excitations (CISDT) and Coupled Cluster Single-Double-Triple (CCSDT) are limited to calculate the performance of these gases because of the presence of large volumes of these compounds with good insulation properties, where the number of heavy particles usually exceeds 10. Such complicated molecular structure results in complicated calculation processes, which indicates that the calculation accuracy and efficiency cannot be guaranteed simultaneously. Based on the consideration of the characteristics of the gas molecular structure and the potential energy of electrons relative to the nucleus, a double-layered composite method with two forms according to the idea of hybridization was proposed with combining the advantages of high precision method and high-efficiency method to overcome the contradiction between calculation efficiency and accuracy. The two methods were respectively entitled as double-layered restricted open-shell model chemistry based on the complete basis set quadratic mode (DL-ROCBS-Q) and double-layered extrapolated CBS limit of electronic energy on the basis of CCSDT with the hierarchical sequence of the correlation-consistent basis sets (DL-RCCSD(T)/CBS) [11].

To comparatively study the relationship between gas molecular structure and its insulation features, the relative dielectric strength (E_r) was used to represent the gas insulating capability. It can be obtained by solving Boltzmann equation or using Monte-Carlo method. From the calculations, it is observed that the collision cross sections between electrons and molecules are required as input parameters, consisting of elastic and inelastic collision, ionization, absorption, electron energy distribution and etc. Nevertheless, some data are still not available both from the measurement and calculation. Based on the above consideration, it is recommended to establish a SAR model that can associate the macroscopic dielectric strength with the microscopic physicochemical parameters of the gas molecule to predict gas dielectric strength. The SAR model was scientifically defined based on the general interaction property's function (GIPF) which the functional form described depends on the property of interest.

Due to the presence of non-covalent interactions (NCIs) between molecules or within a single molecule, which supports to maintain the molecule spatial structure by a dispersed electromagnetic force, a number of physical properties of the gas molecule generally could be determined quantitatively using this GIPF in terms of molecule surface area (A_s) with three quantities Π, σ_{tot}^2 and v that obtained from the surface electrostatic potential, of which Π is the statistical mean deviation of surface electrostatic potential, σ_{tot}^2 is the statistical variance of surface electrostatic potential and v labels a balance degree between positive and negative electrostatic potential [12]. Nevertheless, it is observed from the comparative analysis that surface area contributed by positive electrostatic potential (A_s^+) is highly related to gas dielectric strength rather than the negative electrostatic potential (A_s^-). Besides that, the shape of molecule also affects the interaction between electron and molecule. Therefore, a reduced surface area ($A_{s,r}^+$) was also considered in GIPF, which is defined relating to A_s^+ and molecular ellipticity (O_{val}). Moreover, the molecule density (ρ) was also included in the equation with the effect of molar mass considered. On the basis of multidimensional nonlinear regression analysis, the relationship between gas dielectric strength and molecule structure could be determined by Eq. (1):

$$E_r = 0.299(A_s + 0.783)^2 + 0.922\nu\sigma_{tot}^2 - 1.837\Pi + 0.0391\left(\rho A_{s,r}^+\right)^2 \quad (1)$$

Furtherly, the SAR model was modified with introducing the molecule hardness (η) calculated by O_{val} into GIPF equation to analyse the relationship between gas liquefaction temperature (T_b) and molecule structure, as shown in Eq. (2).

$$T_b = 125.3\Pi^2 - \frac{143.2}{A_s} + \frac{194.7}{\sqrt[3]{\eta}} + 27.0 \quad (2)$$

From the comparison of experiments and calculations of E_r and T_b, as shown in Figure 1, the correlation coefficients from such comparison are respectively 0.993 and 0.985 for E_r and T_b, which indicates that the calculation results using SAR model were in good agreement with the measurements.

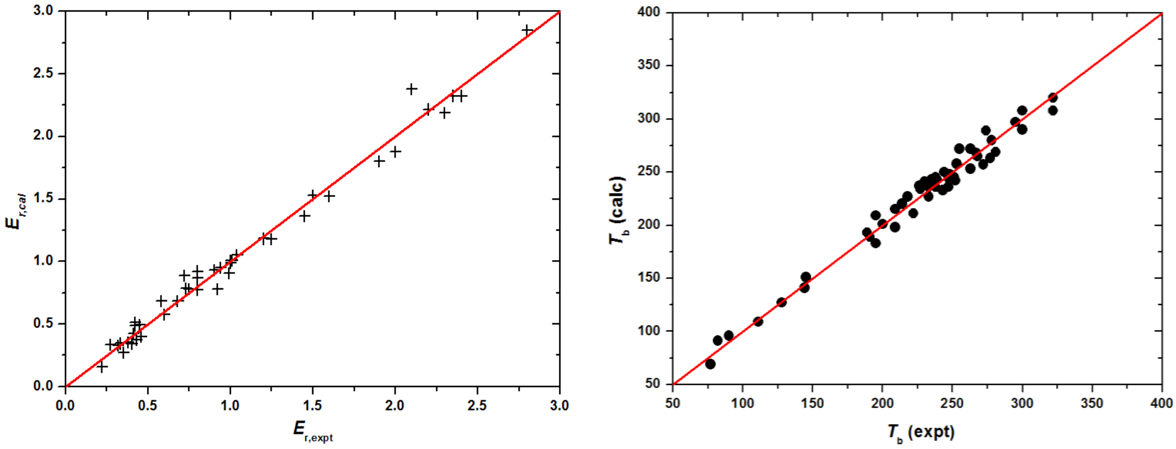


Figure 1 Comparison of predictions and measurments of the gas dielecrtric strength and liquefaction temeprature.

It could be concluded that the established SAR model can accurately predict the gas insulation properties and liquefaction temperature. Besides that, the effects of C_4F_7N molecule structure on the insulating and physicochemical characteristics were thoroughly studied. Since C_4F_7N is usually mixed with the buffer gas, a force field model considering the synergistic effect caused due to the presence of gas mixture was established based on first principles with obtaining the interacting regularity between C_4F_7N and other molecules. The calculated molecule polarity, density and etc. also coincide with the measurements. The configuration of C_4F_7N gas mixture at specific pressure and ambient temperature was finally put forward to support the further use in the UHV GIL prototype.

On the basis of above predictions, considering the impacts of gas molecule structure on its properties, new alternative gases are recommended to be designed and two new ideas for new gas molecule design were proposed according to the changing regularity between molecule structure and gas property obtained from SAR model. The first approach is known as functional group substitution. A variety of groups that considerably improve the insulation strength but insensitive to the liquefaction temperature change were chosen to replace F atom or group of original molecules. The adopted groups should also sufficiently decrease the GWP. The second method is molecular bond hybridization, achieving by the combination of the different segments or groups from two different molecules and new chemical bonds would be formed, especially the unsaturated chemical bonds that improves the chemical stability of the molecule and also considerably decreases the GWP.

3 SYNTHESIS AND PREPARATION OF C_4F_7N

After the analysis of C_4F_7N molecule structure and its effects on the associated properties, the synthesis of C_4F_7N was performed with a thorough consideration of refining and purification. Different synthetic routes were designed and compared with each other. A large batch of industrialized preparation scheme feasible for C_4F_7N was optimized on that basis, which achieves the industrial production of C_4F_7N in China with a purity of more than 99% and it meets the requirements when used in electrical equipment. To firstly achieve the synthesis of C_4F_7N in laboratory, four routes, which are respectively entitling as ketone synthesis, acid synthesis, ester synthesis and anhydride synthesis were designed with various raw materials including oxalyl chloride, heptafluoroisopropyl iodide, methyl chloroformate and isobutyric anhydride. An optimum reaction condition was obtained from a comparison of different synthetic routes. Purification and distillation were also studied with proposing the product quality detection methods such as mass spectrometry (MS), F-NMR spectrum, chromatography, infrared spectrum.

With the comparison of raw material cost, toxicity of intermediate, technological process, difficulty of industrial preparation and application prospect, the anhydride-based electrolytic fluorination approach, which uses mixed anhydride as raw material, was proposed as the synthesis scenario for C_4F_7N industrial preparation. The amplification process was designed to develop a pilot-scale device for electrolytic fluorination with solving the technological problems such as design and manufacturing of electrolytic cell, rectification tower, reaction kettle, characteristic process during chemical production which includes transmission of mass, momentum and thermal with considering the existed chemical reactions, and environmental evaluation. The continuous production process of C_4F_7N was successfully developed by establishing a pilot-scale production line. Meanwhile, the species and volume concentrations of the decomposition products were detected and studied as well. Besides that, the adsorption process due to the presence of impurities was also considered and the controlling standard for evaluating the quality of produced C_4F_7N was then introduced, as shown in Table 1.

Table 1 Impurity type and volume concentration of C_4F_7N production

Impurity	Air	Pentafluoropropionitrile	Hexafluoropropylene	Fluorocarbon	Humidity
Volume concentration	≤ 0.1%	≤ 0.1%	≤ 0.05%	≤ 0.3%	≤ 5 ppmv
Purity：>99.5%（volume fraction）					

4 KEY PERFORMANCE OF C_4F_7N CONCERNED IN ENGINEERING APPLICTAIONS

The discharge tests were carried out with different concentrations of C_4F_7N gas mixture and electrode structures. The insulation characteristics of the discharge phenomenon occurred in the gas gap and along the gas-solid surface were both obtained. The synergistic mechanism of C_4F_7N/CO_2 gas mixture and its effects on the gas insulation performance were also revealed. The insulation design of the environmental UHV GIL filled with C_4F_7N/CO_2 gas mixture was also proposed. Besides that, the compatibilities of C_4F_7N/CO_2 gas mixture with solid materials commonly used in GIL was studied with the considerations of electro-thermal effect.

4.1 Insulation Characteristics of C_4F_7N Mixed with Different Buffer Gases

The discharge parameters of C_4F_7N respectively mixed with N_2 and CO_2 were firstly measured by establishing an experiment platform based on steady-state Thomson (SST) theory. The Electromagnetic shielding is used to ensure the stability and repeatability of the experiments. The experiment reliability is also verified by comparing the measured ionization coefficient (α) and adsorption coefficient (η) of N_2, Ar, He, SF_6 and CO_2 with published references.

Moreover, the breakdown characteristics of C_4F_7N/air, C_4F_7N/N_2 and C_4F_7N/CO_2 mixtures at different voltage waveforms were also assessed with considering of different pressures and mix ratios of gas mixture of which the filling pressure ranges from 0.1 MPa to 0.7 MPa. From the breakdown tests, the impacts of pressure level, mixing ratio, non-uniformity of the electric field and ambient temperature on the breakdown characteristics of C_4F_7N gas mixtures were thouroughly studied as well. By comparing the dieletcric strength of these gas mixtures with SF_6 at uniform electric field under power freqneucy condition, as demonstrated in Figure 2, it is observed that the dielectric strengths of the three C_4F_7N gas mixtures were approximately 60% higher than that of pure SF_6 and grew with the increased C_4F_7N concentration. The dielectric strength of 5%C_4F_7N/95%CO_2 mixture became even higher than 80% of SF_6 at 0.1 MPa.

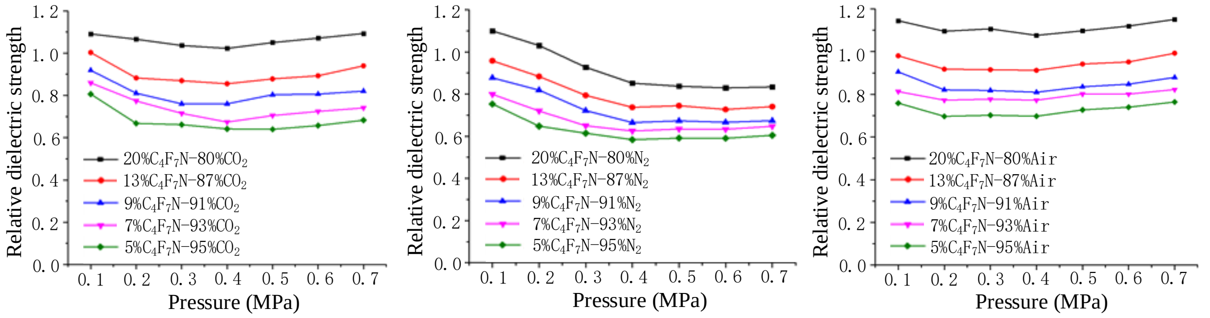


Figure 2 Relative dielectric strength of C_4F_7N/CO_2, C_4F_7N/N_2 and C_4F_7N/Air in comparison with SF_6 under power frequency.

By comparing the dieletcric strength of these gas mixtures with SF_6 at slightly uneven electric field, as presented in Figure 3, it is observed that the dielectric strengths of C_4F_7N/CO_2 and C_4F_7N/air mixtures were both higher than 60% of pure SF_6 while that of C_4F_7N/N_2 presents a overall lower distribution.

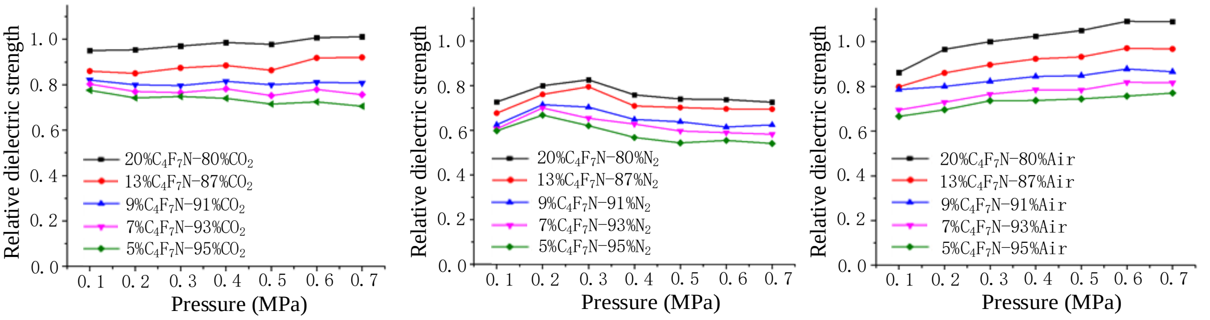


Figure 3 Relative dielectric strength of C_4F_7N/CO_2, C_4F_7N/N_2 and C_4F_7N/Air in comparison with SF_6 under lightning pulse.

Based on the above findings, it can be concluded that the dielectric strength of gas mixtures with a same concentration of C_4F_7N presents a decrease manner respectively for air, CO_2 and N_2, which means that N_2 is not suitable to be used as a buffer gas to mix with C_4F_7N. Furthermore, the breakdown voltage of C_4F_7N/CO_2 and C_4F_7N/air mixtures also nonlinearly increases with the grown gas mixing ratio and the corresponded value of the gas mixture was also larger than the weighted average value of two individual gases, indicating the synergistic effect, as shown in Figure 4.

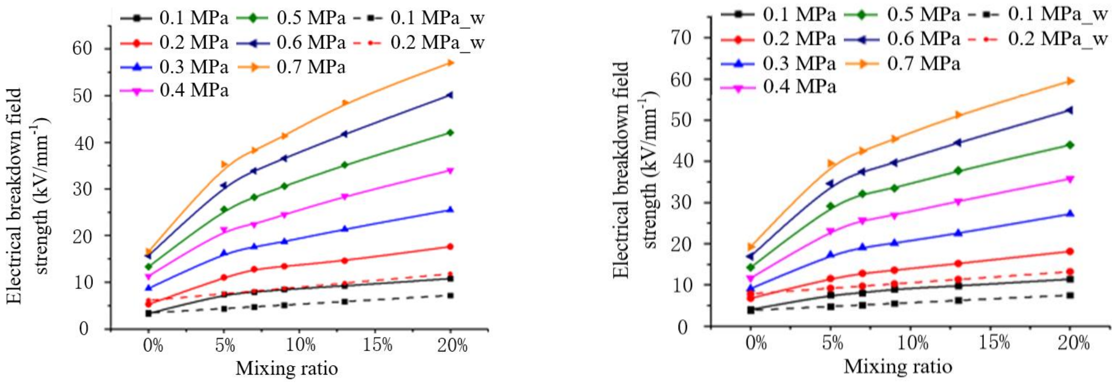


Figure 4 Electcrical breakdown field strength of C_4F_7N/CO_2 and C_4F_7N/Air at different mixing ratios and pressures.

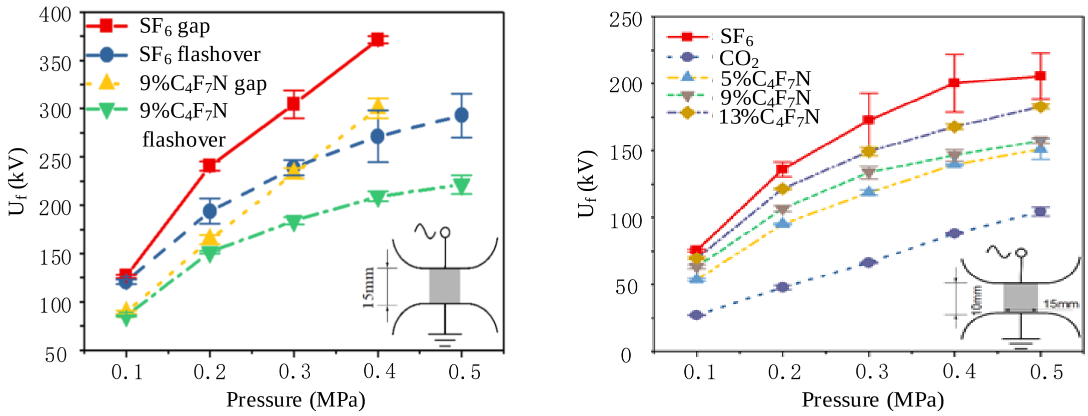
For the dielectric strength of the gas mixtures under the effects due to the presence of impulse voltage, it is found that the breakdown voltage U_b of C_4F_7N/CO_2 presented a linearly increase with the increase of pressure both at a uniform and a slightly uneven distributions of the electric field. In addition, the positive breakdown voltage of C_4F_7N/CO_2 and C_4F_7N/N_2 mixtures also became higher than that of the negative breakdown voltage.

Generally speaking, C_4F_7N/CO_2 mixture is more suitable than C_4F_7N/N_2 and C_4F_7N/air by analysing the influences of multiple factors on the gas insulation performance. Although the insulation performance of C_4F_7N/CO_2 and C_4F_7N/air seems comparable, the complexity of operation and maintenance will be increased since C_4F_7N/air is a kind of ternary mixture which includes O_2. Besides that, C_4F_7N/CO_2 mixture has a higher dielectric strength when local electric field somewhere becomes stronger. Based on the requirements that the actual ambient temperature should not be higher than -15 ℃, it is recommended that the gas configuration be used in the UHV GIL with a filling pressure of 0.7 MPa and

9% volume concentration of C_4F_7N, taking into account the synergistic effect, in order to satisfy its insulation performance during the operation. For such optimized gas configuration, the 50% breakdown electric field strength was obtained by a numerical model established that considers the effects of pressure and mixing ratio of gas, voltage waveform and polarity applied within the gas gap under the slightly uneven electric field distribution. The maximum value of 50% breakdown electric field strength can thus be determined using an empirical formula shown as below:

$$E_{\max}\,(k = 9\%) = 17.08(10p)^{0.6239} d^{-0.078} \tag{3}$$

where p is the pressure from 0.1 MPa to 0.7 MPa and d is the gap distance from 2.5 mm to 37.5 mm. Surface flashover characteristics of C_4F_7N/CO_2 mixture under different operation conditions were also experimentally taken into account in the present work with obtaining the effects of pressure and mixing ratio of the gas mixture on the peak value of the surface flashover voltage, as presented in Figure 5. The experimental results show that the 50% gap breakdown voltage increases with pressure growing and it was gradually deviated from the Paschen's curve. Under same experiment conditions, while the insulator was included within the gap, the electric field was distorted at triple junction point where the electrode, insulator and gas medium meet with each other. The electron avalanche became more likely to occur due to the existence of a stronger local electric field, which leads to flashover along the insulator surface and the flashover voltage lower than the gap breakdown voltage. Meanwhile, with the increase of C_4F_7N concentration, the flashover voltage gradually grew with a saturation trend. If the insulation performance of the gas medium is required to be stronger than SF_6, the filling pressure of 0.6 MPa and 0.7 MPa are suitable for $9\%C_4F_7N/91\%CO_2$ mixture to replace the SF_6 under 0.5 MPa.



(a) Gap breakdown voltage and flashover voltage (b) Surface flashover voltage with pressure

Figure 5 Experimental results of surface flashover voltage at the gas-solid interface for C_4F_7N/CO_2, CO_2 and SF_6.

It should be mentioned that the surface insulation design is a constraint, and its requirement to withstand the lightning impulse becomes more critical. Considering the polarity effect, it is mainly determined by the surface flashover voltage under negative lightning impact. Based on the control value of SF_6 insulation design, the allowable electric field strength for gap and surface of $9\%C_4F_7N/91\%CO_2$ is slightly higher, as shown in Table 2.

Table 2 The allowable electric field strength for C_4F_7N/CO_2 and SF_6

Gas	Control value for gap	Control value for surface
0.5 MPa SF_6	24 kV/mm	12 kV/mm
0.7 MPa $9\%C_4F_7N$	26.4 kV/mm	14.7 kV/mm

4.2 Compatibility Between Gas-Solid Surface

For solid materials such as metal (copper and aluminium), epoxy resin and rubber, to which C_4F_7N would be attached inside the electrical equipment, discharge and overheating tests were respectively conducted, and the effects of gas mixing ratio, applied voltage, electrode material, experiment duration on the decomposition characteristics of C_4F_7N/CO_2 were also considered. The characteristic products and their change regularities were obtained including CO, CF_4, C_3F_6 and nitriles. On that basis, associated electro-thermal acceleration tests were designed to study the compatibility between gas-solid surface. The temperature and the electric field strength during the tests were respectively set to 112 ℃

and 2.4 kV/mm. After tests, the chemical parameters such as gas composition, decomposition product and solid surface element, the mechanical parameters such as compressive stress relaxation and compression permanent deformation, and also the electrical parameters such as dielectric constant of insulation materials and surface flashover voltage were detected with corresponding methods. Through in-depth analysis of C_4F_7N/CO_2 mixture decomposition, the indicators for assessing the compatibility between C_4F_7N/CO_2 mixture and the solid materials were proposed, as shown in Table 3.

The test results show that both metal and epoxy resin have good compatibility with C_4F_7N while the gas was hydrolysed in the alkaline environment provided by epDM additives, resulting in the compatibility between C_4F_7N and epDM. Therefore, fluoro-rubber recommended to be used as the sealing material.

Table 3 Indicators for evaluation of gas-solid compatibility

Assessment indicator	Indicator for gas	Indicator for solid
Good	No new compositions were detected by the instrument.	No material difference after test in C_4F_7N/CO_2 mixture and He gas environment.
	The proportion of C_4F_7N does not change by more than 1%.	Rubber : change of compression permanent deformation rate with temperature is not more than 1%; Epoxy resin : flashover voltage after test should not be less than 90% of the flashover voltage along the original sample.
With compatibility issues	New compositions were detected by the instrument.	The insulating gas reacts with solid material on the interface and produces decomposition products.
	The proportion of C_4F_7N gas changes more than 1%.	The properties of the material tested in C_4F_7N/CO_2 mixture and He gas are obviously different and the material properties do not satisfy the utilisation requirements.

5 DEVELOPMENT AND MAINTENANCE OF THE UHV ENVIRONMENTAL GIL

Following the thorough understanding of C_4F_7N gas mixture, the comprehensive optimization design of insulation, gas flow, sealing and structural strength of the 1000 kV UHV environment-friendly GIL was put forward to meet the operation requirements. The UHV GIL prototype with C_4F_7N/CO_2 gas was firstly developed all over the world with passing the type tests and electrification tests. The inner diameter and the length of the GIL prototype are respectively 880 mm and nearly 27.5 mm. Key components such as insulators and pipeline prototypes of this environmental GIL is well-designed with adaptability of using C_4F_7N/CO_2 mixture, breaking large size, low margin, high strength and complex characteristics of gas technology bottleneck of UHV grade. The maintenance technologies such as fault monitoring and detection has been set up to ensure the safe and reliable operation.

5.1 Development of 1000 kV UHV Environmental GIL

Optimization design was carried out for the support insulators in the GIL. The maximum surface electric field strength of insulator and shielding part was reduced. The basin type and tri-post insulators were optimised to satisfy the constraints of mechanical properties and heat dissipation. It is observed that the maximum electric field strength in C_4F_7N/CO_2 environment after the optimisation is reduced, as shown in Table 4, which makes the overall electric field distribution more uniform.

Table 4 Comparison of the electric field strength before and after the optimisation.

Insulator type	Key position	Before optimisation	After optimisation	Allowable value
Basin-type insulator	Shielding surface	22.34	20.18	26.4
	Surface along insulator	10.51	10.09	14.7
	Insert surface (power frequency)	3.24	2.8	3~4

Tri-post insulator	Insulator surface	12.13	11.36	14.7
	Connecting cylinder surface	19.86	21.62	26.4
	Insert surface (power frequency)	3.28	3.37	3~4

According to the test method of UHV GIS/GIL insulators in SF_6 gas environment, the corresponding test method of insulators in C_4F_7N/CO_2 mixture inside the 1000 kV environmental GIL was proposed combined with the characteristics of C_4F_7N/CO_2 mixture and the technical conditions of this environmental GIL. The allowance test for power frequency voltage, compatibility test and surface tolerance test for insulator were included as well with adjusting the changed experiment parameters and methods resulted from the pressure increase. The basin-type and tri-post insulators with high performance in C_4F_7N/CO_2 mixture environment were developed and passed the experimental evaluation.

According to the physical-chemical properties, insulation characteristics and gas-solid compatibility of C_4F_7N, considering the sensitivity of the gas working medium to the electric field non-uniformity and environmental protection, the gas configuration of 9%C_4F_7N/91%CO_2 with a filling pressure of 0.7 MPa was proposed for using in 1000 kV environmental GIL. The technical parameters of the prototype were determined by referring to SF_6. The rated voltage and current are respectively 1100 kV and 6,300 A. The overall structure of this 1000 kV environmental GIL was determined based on the principles of production standardization and modular design, as shown in Figure 6.

With the consideration of pressure growth from 0.5 MPa to 0.7 MPa and the material properties variation of C_4F_7N/CO_2 mixture, the temperature rise and structural strength of the UHV GIL were calculated and ~~checked~~compared with the reference values from the standards, which presents a sufficient allowance on the basis of ensuring the economic benefit of the product. The radial temperature distribution of the pipeline was obtained and the results show that long size of the conductor and the shell thickness meet the equipment requirements. The sealing material was replaced by fluoro-rubber for the convex and concave structures of the T-shape sealing groove which was designed with embedded double-channel and anti-shedding. The annual gas leakage rate is less than 0.01%. The environmental GIL filled with C_4F_7N/CO_2 mixture was finally developed and performed the live test at the UHV AC test base in Wuhan, as shown in Figure 7.

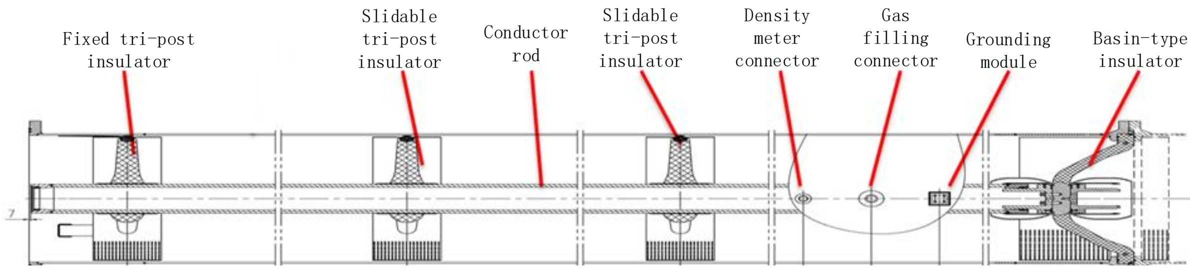


Figure 6 Schematic diagram of the 1000 kV environmental GIL prototype.

Figure 7 Live test of 1000 kV environmental GIL prototype at UHV AC test base.

5.2 Maintenance of 1000 kV UHV Environmental GIL

Based on the optical detection method for partial discharge, an embedded fluorescence optical fiber was combined with the UHF detection technology so that the PD could be detected using such photo-electric detection approach with high sensitivity. The reasonable method for locating the fault induced by arc discharge was also put forward. To eliminate the effects due to the presence of particles, the detection based on ultrasonic amplitude-time of flight spectra was introduced. The stairwell-pressurisation-based dielectric withstand voltage test was formulated for particle sophistication, as shown in Figure 8. The voltage amplitude and duration of the test were optimised to drive the particles moving towards the trap.

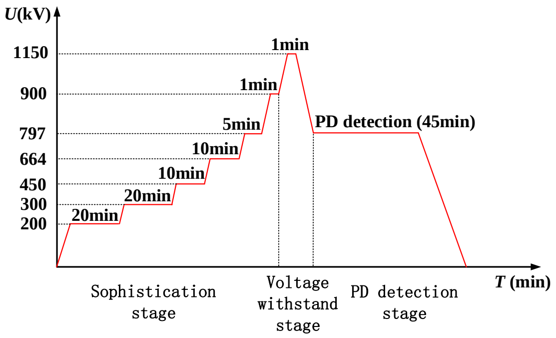


Figure 8 Dielectric withstand voltage test for particle sophistication.

For the detection and handling of C_4F_7N/CO_2 mixture during operation, the gas mix ratio can be obtained by the combination of infrared spectroscopy and micro-thermal conductivity detecting technology. The micro-leakage of C_4F_7N was detected based on non-dispersive infrared (NDIR) technology and the gas composition was determined by gas chromatograph with helium ionization detector. Moreover, the gas states were detected by developing a serialized and high-precision device with multi-characteristic inputs. Dynamic gas distribution and filling devices were also developed to support the environmental GIL operation.

6 CONCLUSIONS

From the systematic research, the following conclusions can be drawn:

(1) Rapid and accurate calculation method for gas molecule structure and energy was introduced to create a SAR model to analyse the relationship between molecule structure and key characteristics of gas insulation and liquefaction. Correlation between macro properties and microstructure of the insulating gas was revealed from the study. On that basis, two new methods for environmental gas structure design were proposed, which was also applicable to the design of C_4F_7N.

(2) The synthesis route of C_4F_7N was proposed and electrolytic-fluorination-based preparation method was designed to realize the industrial preparation of C_4F_7N with a purity higher than 99.5%.

(3) The gap and surface discharge regularity of C_4F_7N and its mixtures were experimentally studied and the gas configuration scheme was optimised. The allowable electric field strength of 9%C_4F_7N/91%CO_2 at 0.7 MPa was proposed. From the compatibility study, it is recommended that fluoro-rubber is more suitable as the sealing material.

(4) Based on the SF_6 insulation design, the supporting insulator structure was optimized and the UHV environmental GIL filling with C_4F_7N/CO_2 gas mixture was developed to solve the problems of operation and maintenance, gas detection and handling problems to ensure GIL reliable operation. Therefore, it is technically feasible to choose C_4F_7N/CO_2 mixture for SF_6 substitution.

(5) On the basis of the obtained insulation properties of C_4F_7N/CO_2, the interruption performance evaluation of C_4F_7N/CO_2 gas mixture still needs further study, especially considering the adjustment of the interrupting chamber design and the characteristics of the driving mechanism.

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