Investigation of Synthesis and Dielectric Properties of c-C$_4$F$_8$O With Its CO$_2$/N$_2$ Mixtures as SF$_6$ Alternatives in Gas-Insulated Applications

ZHANYANG GAO[1], YI WANG[1], SHIYAO WANG[1], RUICHAO PENG[1], WENJUN ZHOU[2], PING YU[1], AND YUNBAI LUO[1]

[1]Engineering Research Center of Organosilicon Compounds & Materials, Ministry of Education, College of Chemistry and Molecular Sciences, Wuhan University, Wuhan 430072, China
[2]School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China

Corresponding author: Yunbai Luo (ybai@whu.edu.cn)

ABSTRACT The usage and emission of SF$_6$ has been regulated because of high Global Warming Potential (GWP) and long atmospheric lifetime as an insulator in high voltage power transmission equipment. This paper proposes c-C$_4$F$_8$O and its mixtures as a substitute for SF$_6$ with low GWP and superior insulation performance. c-C$_4$F$_8$O is synthesized by 1,4-diiodoperfluorobutane and fuming sulfuric acid with the yield of 55.7% under optimal conditions. The GWP of c-C$_4$F$_8$O is about one-third that of SF$_6$ and its dielectric strength is about 1.2-1.4 times that of SF$_6$. CO$_2$ and N$_2$ are mixed with c-C$_4$F$_8$O to lower liquefaction temperature and GWP. The investigation of breakdown voltage and self-recoverability of gas mixtures has shown that the insulation performance and stability of c-C$_4$F$_8$O-N$_2$ is better than c-C$_4$F$_8$O-CO$_2$ mixtures. The decomposition process of c-C$_4$F$_8$O might produce some nonflammable or inexplosive by-products, such as C$_2$F$_4$, c-C$_2$F$_4$O, c-C$_3$F$_6$ and CF$_2$O simulated by Gaussian 09. The results indicate that c-C$_4$F$_8$O and N$_2$ mixtures have potential to replace SF$_6$ in electrical equipment.

INDEX TERMS Synthesis, perfluorotetrahydrofuran, insulation performance, sulfur hexafluoride substitutes.

I. INTRODUCTION

SF$_6$ has been widely used in the gas insulated switchgear (GIS) and gas insulated lines (GIL) due to its superior features, such as outstanding dielectric strength, low liquefaction temperature, excellent chemical stability and self-recoverability. But high GWP (about 23500 times that of CO$_2$) and long atmospheric lifetime makes SF$_6$ be classified as the most potent greenhouse gas and its emission has been restricted by the Kyoto Protocol [1]–[3]. Based on this, many measures have been devoted to controlling the usage of SF$_6$, especially in electricity industry. Although some power companies employed mixture of SF$_6$ and N$_2$ as insulation gas to alleviate the greenhouse effect without impacting

insulation properties, environmental effect cannot be ignored in the case of a large number of SF$_6$ [4]–[6]. Consequently, finding suitable replacement gases for SF$_6$ is of vital importance to the environment.

To address the issue, many alternative gases and gas mixtures with low GWP have been researched, such as N$_2$, CO$_2$, CF$_3$I and C$_4$F$_7$N (heptafluoroisobutyronitrile) *et al*. The dielectric strength of air, N$_2$ and CO$_2$ is about one-third that of SF$_6$ and can only be used in low voltage electrical equipment [7], [8]. For instance, 24 kV GIS with N$_2$, as the environment-friendly insulating medium, has been commercialized. In 2008, H. Katagiri and co-workers proposed that CF$_3$I was possible to replace SF$_6$ with the dielectric strength of mixture CF$_3$I (30%) and CO$_2$(70%) achieving 0.75~0.80 times that of SF$_6$ in 0.1 MPa and boiling point of mixtures about −12 °C in 0.5 MPa [9]. However, CF$_3$I

FIGURE 1. The geometry structure molecule of $c\text{-}C_4F_8O$.

FIGURE 2. The testing circuit of power frequency breakdown.

might generate iodine under discharge condition along with reducing the insulation performance of equipment [10]–[12]. Currently, Minnesota Mining and Manufacturing and General Electric Company put forward a g3 gas, mixture of C_4F_7N with CO_2 [1], [13], a new eco-friendly candidate in terms of remarkable insulation performance and low greenhouse effect but decomposition products are toxic [14], [15], which limited its application to some extent. Wang and Luo's groups focus on predicting and synthesizing insulation gases [16]–[19]. In our recent studies, the perfluorotetrahydrofuran ($c\text{-}C_4F_8O$) is recommended as an insulation medium, which is initially used as a plasma-enhanced chemical vapor deposition (PECVD) chamber cleaning gas with characteristics of nonflammability, low-toxicity and good chemical resistance [20]. The geometry structure molecule of $c\text{-}C_4F_8O$ is shown in Fig. 1. In addition, the GWP value of $c\text{-}C_4F_8O$ at 8700 is about one-third that of SF_6 and its ozone depletion potential (ODP) is 0. Therefore, as a potential substitute for SF_6, the synthesis and study of insulation properties of $c\text{-}C_4F_8O$ is more important.

Several strategies have been employed to exploit the synthesis $c\text{-}C_4F_8O$, such as electrofluorination, fluorine cyclization et al. For example, Edward A. Kauck used tetrahydrofuran and anhydrous hydrogen fluoride as reactants under electrolysis conditions to prepare $c\text{-}C_4F_8O$ [21]; In Frick and Navy's route, $c\text{-}C_4F_8O$ was produced by perfluoroglutaryl fluoride and fluorine [22]. Nevertheless, all above methods were difficult to be applied in large scale owing to complex reaction conditions and high toxicity of raw materials. From a viewpoint of green chemistry, searching for an efficient and simple way to synthesize $c\text{-}C_4F_8O$ was significant. In 1976, M. Yamabe proposed a new way of using fuming sulfuric acid and 1,4-diiodoperfluorobutane to prepare $c\text{-}C_4F_8O$ with reasonable yield [23].

On the basis of previous research, we optimized reaction condition and synthesized $c\text{-}C_4F_8O$ from 1,4-diiodoperfluorobutane and fuming sulfuric acid. Then, the dielectric strength of $c\text{-}C_4F_8O$ was investigated from 0.100 to 0.225 MPa. Nevertheless, boiling point of $c\text{-}C_4F_8O$ was about 0 °C in 0.100 MPa and it was almost impossible to employ pure $c\text{-}C_4F_8O$ as insulation gas without other buffer gas. Herein, we tested the breakdown voltage of $c\text{-}C_4F_8O$ and N_2 or CO_2 mixtures and properties of these mixtures in environmental, chemical and physical aspects were also

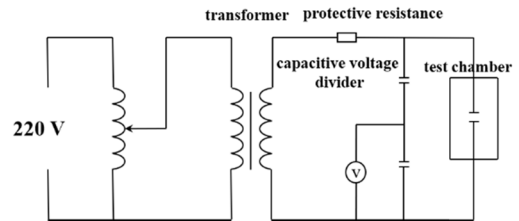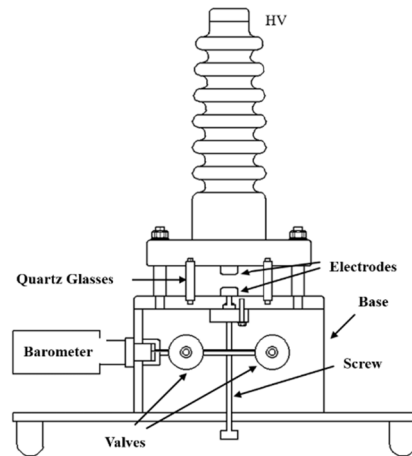**FIGURE 3.** Device of power frequency breakdown.

discussed. Finally, the decomposition mechanism of $c\text{-}C_4F_8O$ was simulated by Gaussian 09.

II. MATERIAL AND TEST PLATFORM
A. MATERIALS AND GENGERAL MEASUREMENTS
Fuming sulfuric acid of containing 50% SO_3 was received from Yangzhou Hubao chemical reagents company; 1,4-diiodoperfluorobutane was purchased from Tokyo chemical industry Co., LTD.

GC-MS was recorded on a Varian-450 Gas Chromatograph coupled to a Varian-320 Mass Selective Detector equipped with EI detectors. The Gas Chromatograph was equipped with a 30 m and 0.25 mm, 0.25 mm df and VF-5 column. IR spectra was recorded on a Thermo FT-IR 5700 IR (KBr).

B. TEST PLATFORM
Fig.2 showed the testing circuit of power frequency breakdown. The input voltage of transformer was 220 V and maximum output was 50 kV AC. The protective resistance in the circuit was 5 kΩ and the voltage divider ratio of the capacitive voltage divider was 1000:1.

Fig.3 showed the device of power frequency breakdown. The shell was sealed by quartz glasses and electrodes were made of Tungsten-Copper alloy. Plate-plate electrodes with a diameter of 20 mm were used in the test. The electric field was uniform and the coefficient of uniformity was about 1. The electrodes gap was 3 mm. The electrodes were polished by abrasive paper in 5000 mesh and cleaned by anhydrous alcohol before the test.

Z. Gao et al.: Investigation of Synthesis and Dielectric Properties of c-C$_4$F$_8$O With Its CO$_2$/N$_2$ Mixtures as SF$_6$ Alternatives

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C. CALCUATION METHOD

The simulation of decomposition mechanism of c-C$_4$F$_8$O was performed with Gaussian 09 software [24], molecules geometries were optimized by B3LYP/6-31G(d,p) [25]–[28]. In order to evaluate the thermodynamic stability of different molecules, normal vibration mode analysis was performed, and the vibration free energy at 298 K were estimated to predict the reaction free energy of the radical decomposition.

III. EXPERIMANTAL SECTION

A. SYNTHESIS OF c-C$_4$F$_8$O

17.8 g of fuming sulfuric acid of containing 50% SO$_3$ were poured into 100 mL three-neck flask that was equipped with constant pressure dropping funnel, reflux condenser and dry-ice cold trap, then 4.6 g 1,4-diiodoperfluorobutane were added dropwise with the same temperature of 80 °C and continuously stirred for 6 h. Finally, 1.2 g c-C$_4$F$_8$O was obtained with a yield of 55.7% and structures were confirmed by GC-MS and FT-IR.

GC/EI/MS retention time, m/z: 1.727 min, 69.0 (CF$_3$-), 99.9 (-CF$_2$-CF$_2$-), 149.9 (-CF$_2$-CF$_2$-CF$_2$-), 168.9 (-CF$_2$-CF$_2$-CF$_3$).

IR: Vc-o-c=1094.50 cm^{-1}, 1204.29 cm^{-1}, 1260.72 cm^{-1}.

B. BREAKDOWN VOLTAGE OF c-C$_4$F$_8$O AND ITS MIXTURES

The vessel needed to be evacuated and cleaned three times before the target gas was filled. The step-up method was taken in the test of power frequency breakdown. Firstly, a breakdown voltage U_0 was obtained in the test. In subsequent experiments the voltage was rapidly rising to 75% of U_0, then was up to breakdown voltage U at a rate of 2%~3% U_0/s with interval of 3 min between the two tests. Each test was repeated 10 times and the average value was taken as the breakdown voltage. The power frequency voltage was the voltage of the sinusoidal waveform, and the effective value was multiplied by $\sqrt{2}$ to equal the peak value.

IV. RESULTS AND DISCUSSION

A. EFFECTS OF REACTION CONDITIONS ON c-C$_4$F$_8$O YIELD

The reaction between **1** and fuming sulfuric acid were influenced by some factors, such as reaction temperature and the molar ratio of SO$_3$ to **1**. As shown in Table 1, the yield of **2** was found to increase from 32.3% to 42.3% as the reaction temperature increased from 60 °C to 80 °C. However, the yield was falling rapidly to 36.7% with further increase in the temperature attributing to production of more by-products. In addition, the molar ratio of SO$_3$ to **1** also affected the yield of **2** and reaction rate. The yield of **2** was gradually improved with the molar ratio of SO$_3$ to **1** from 8:1 to 11:1. The conversion of **1**remained stable when the molar ratio of SO$_3$ to **1** continuously increased from 11:1 to 13:1. Therefore, the yield of **2** was 55.7% when the molar ratio of SO$_3$ to **1** was 11:1 at 80 °C.

TABLE 1. Optimized conditions for synthesis of c-C$_4$F$_8$O.

I(CF$_2$)$_4$I $\xrightarrow[\text{H}_2\text{SO}_4]{\text{SO}_3}$

1 **2**

Entry	T/°C^a	SO$_3$:1^b	Yield/%^{c}
1	60	8:1	32.3
2	70	8:1	38.7
3	80	8:1	42.3
4	90	8:1	40.5
5	100	8:1	36.7
6	80	9:1	45.7
7	80	10:1	50.3
8	80	11:1	55.7
9	80	12:1	55.2
10	80	13:1	55.8

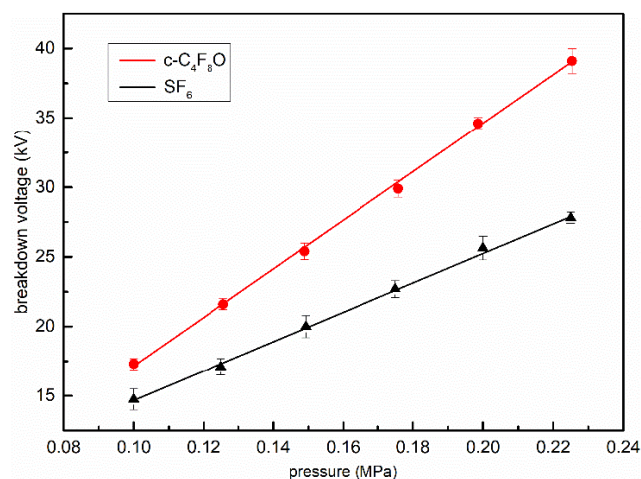^{a} Reaction temperature; ^{b} The molar ratio of SO$_3$ to 1; ^{c} Isolated yield.

FIGURE 4. Pure c-C$_4$F$_8$O and SF$_6$ gases power frequency insulation performance in quasi-uniform electric field.

B. BREAKDOWN CHARACTERISTICS OF c-C$_4$F$_8$O UNDER AC

Fig. 4 showed the insulation performance of pure c-C$_4$F$_8$O and SF$_6$ under different pressures (the pressure was absolute pressure) in quasi-uniform electric field. The dielectric strength of c-C$_4$F$_8$O was similar to that of SF$_6$, showing almost linear upward trend with increase in the pressure from 0.100 to 0.225 MPa, but the growth rate was significantly higher than that of SF$_6$. For example, the breakdown voltage of c-C$_4$F$_8$O and SF$_6$ was 17.3, 25.4, 39.1 kV and 14.8, 20.0, 27.8 kV respectively in 0.100, 0.150, 0.225 MPa. Based on testing results, the breakdown voltage of c-C$_4$F$_8$O was 1.17, 1.24 and 1.40 times that of SF$_6$ respectively and it also indicated excellent insulation performance of c-C$_4$F$_8$O. If the pressure continuously increased in the chamber, the gas would be liquefied attributing to lower saturated vapor pressure. In other words, when pure c-C$_4$F$_8$O was used as
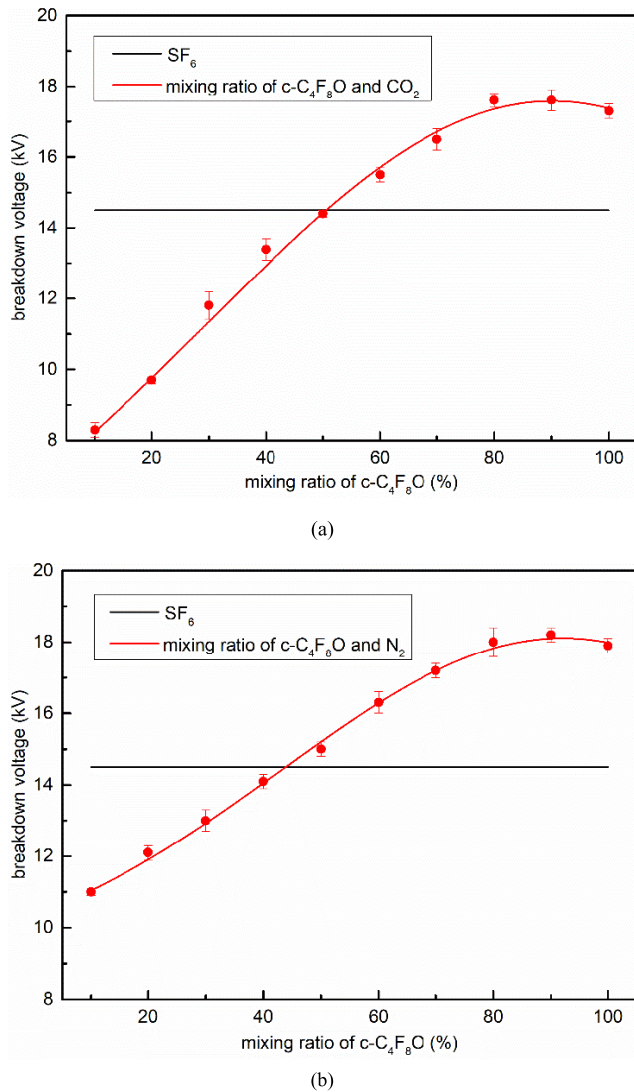
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(a)

(b)

FIGURE 5. Insulation performance of c-C$_4$F$_8$O mixtures in quasi-uniform electric field at 0.1 MPa.(a) mixture of c-C$_4$F$_8$O and CO$_2$; (b) mixture of c-C$_4$F$_8$O and N$_2$.

insulating gas, the application environment would be greatly restricted. Therefore, insulation properties of mixture of c-C$_4$F$_8$O and CO$_2$ or N$_2$ were also investigated.

C. BREAKDOWN CHARACTERISTICS OF MIXTURE OF c-C$_4$F$_8$O AND CO$_2$/N$_2$ UNDER AC

Fig.5 demonstrated the relationship between the mixing ratio of c-C$_4$F$_8$O in gas mixture at 0.100 MPa and its dielectric strength. As shown in Fig.5(a), the breakdown voltage of c-C$_4$F$_8$O and CO$_2$ mixture was improved obviously with the increase of c-C$_4$F$_8$O content. The breakdown voltage of 10% c-C$_4$F$_8$O-90% CO$_2$ was about 60% that of pure SF$_6$ in 0.100 MPa (The black line means breakdown voltage of pure SF$_6$). When the mixing ratio of c-C$_4$F$_8$O gradually increased to 50%, the breakdown voltage of gas mixture was about equal to that of SF$_6$.

The insulation performance of c-C$_4$F$_8$O/N$_2$ was also investigated at the same condition. Fig.5(b) indicated that

TABLE 2. Synergistic effect of c-C$_4$F$_8$O and CO$_2$/N$_2$ in 0.1 MPa.

k	C(c-C$_4$F$_8$O/CO$_2$)	C(c-C$_4$F$_8$O/N$_2$)
0.1	0.312	0.116
0.2	0.304	0.139
0.3	0.189	0.131
0.4	0.131	0.096
0.5	0.083	0.065
0.6	0.044	0.024
0.7	0.016	0.001
0.8	-0.004	-0.009
0.9	-0.002	-0.007

breakdown voltage of c-C$_4$F$_8$O/N$_2$ was increased from 0.76 to 1.21 times that of pure SF$_6$ as the mixing ratio of c-C$_4$F$_8$O increased from 10% to 90% (The black line means breakdown voltage of pure SF$_6$). When the mixing ratio of c-C$_4$F$_8$O was about 44%, the breakdown voltage of gas mixture was nearly equal to that of SF$_6$. However, it was noteworthy that the breakdown voltage of 90% c-C$_4$F$_8$O/CO$_2$ was higher than that of pure c-C$_4$F$_8$O in Fig.5 probably because of synergistic effect of c-C$_4$F$_8$O and CO$_2$/N$_2$. Hence, the synergistic influence was studied.

D. SYNERGISTIC EFFECT OF c-C$_4$ F$_8$O AND CO$_2$/N$_2$ MXITURES

The breakdown voltage of c-C$_4$F$_8$O and CO$_2$/N$_2$ mixtures was not linear growth with the increase in concentration of c-C$_4$F$_8$O and this non-linearity was referred to as synergistic effect. The synergistic effect could be defined by the following formula [29]:

$$V_m = V_2 + k\,(V_1 - V_2)\big/[k + (1 - k)\,C] \qquad (1)$$

V_m was breakdown voltage of the gas mixture; V_1 and V_2 were the breakdown voltages of pure gases 1 and 2($V_1 > V_2$); k was the mixing ratio and C was a constant. When $C > 1$, it indicated negative synergistic effect; When $C = 1$, it indicated that V_m linearly changed with increase in the value of k; When $0 < C < 1$, it indicated synergistic effect; When $C < 0$, it indicated positive synergistic effect.

Table 2 provided synergistic effect of c-C$_4$F$_8$O and CO$_2$/N$_2$ and values of C in 0.100 MPa. When the mixing ratio raised from 0.1 to 0.7, values of C were greater than 0 and less than 1, showing synergistic effect. As the proportion of c-C$_4$F$_8$O in the gas mixture was continuously increased, the value of C turned into negative, meaning that mixture of c-C$_4$F$_8$O and CO$_2$/N$_2$ showed positive synergistic effect. This also explained the phenomenon that breakdown voltage of 80%~90% c-C$_4$F$_8$O-CO$_2$/N$_2$ was higher than that of pure c-C$_4$F$_8$O.

E. LIQUEFACTION TEMPERATURE OF MIXTURE OF c-C$_4$F$_8$O AND N$_2$

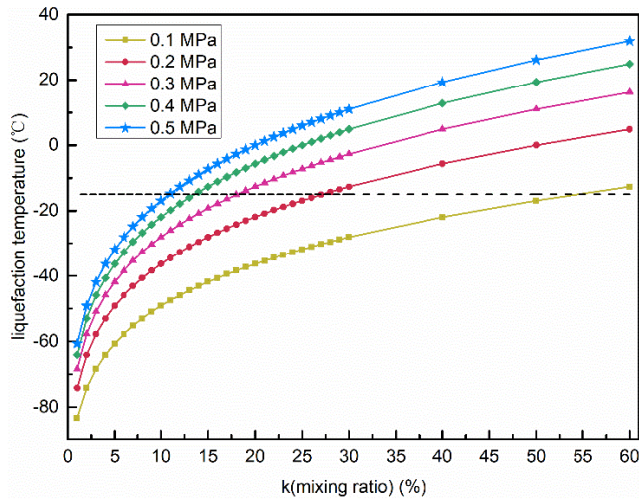SF$_6$ could be widely used in the high voltage apparatus because of remarkable insulation performance and low

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FIGURE 6. Boiling point of gas mixture with mixing ratio (k) of c-C_4F_8O.

FIGURE 7. Total GWP for c-C_4F_8O mixtures.

liquefaction temperature. However, boiling point of c-C_4F_8O was so high, about 0 °C in 0.1 MPa, that it couldn't be used alone as an insulation medium and must be mixed with buffer gas, such as N_2, CO_2. Mixture of c-C_4F_8O and N_2 was selected as the main focus in this study. According to previous reports, the saturated vapor pressure of c-C_4F_8O was 240.34 Kpa at 25 °C and boiling point was 0 °C. The relationship between vapor pressure (P_v/Mpa) and boiling point (T_b) could be described by the following equation [30] $A = 87$ J/mol•k; $R = 8.3$ J/mol•k:

$$P_V = 1/10exp[A(1 - T_b/T)/R] \tag{2}$$

An assumption was made that gas was ideal and liquefaction temperature of mixtures could be obtained by:

$$T_{mb} = T_b/1 - ln(10kP_V)/10.5 \tag{3}$$

k was the mixing ratio of c-C_4F_8O for a total pressure.

Fig.6 showed boiling point of gas mixture under different mixing ratios and pressures. The liquefaction temperature of gas mixture increased along with the addition of c-C_4F_8O under the same pressure. When the dosage of c-C_4F_8O remained the same, the liquefaction temperature of gas mixture was also raised with pressure from 0.1 MPa to 0.5 MPa. As was previously reported, -15 °C was the minimum operation temperature for medium-voltage GIS [31]. The mixing ratio of c-C_4F_8O should be no more than 55%, 27%, 18%, 14% and 11% in 0.1, 0.2, 0.3, 0.4 and 0.5 MPa respectively. If the c-C_4F_8O was used in insulation equipment with some pressures, the proportion shall not exceed 20%.

F. GWP FOR MIXTURE OF c-C_4F_8O AND CO_2/N_2
The GWP of c-C_4F_8O was 8700, about one-third of SF_6 but it was relatively high for the power industry. The GWP of c-C_4F_8O and CO_2/N_2 mixtures were investigated to ease the environmental impact. In 2006, Official Journal of the European Union reported a method of calculating the total
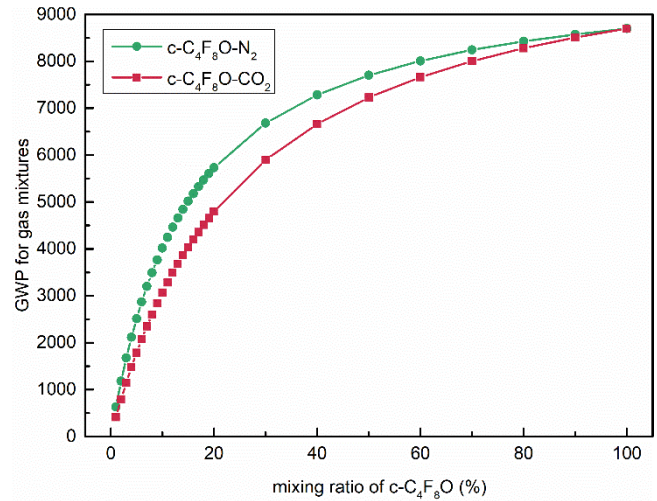
GWP for gas mixtures by the following equation [32]:

$$\sum GWP = (X\% * GWP) + (Y\% * GWP) + \ldots(N\% * GWP) \tag{4}$$

where X%, Y% . . . N% was the mass fraction of the gaseous mixture of X, Y . . . N respectively.

Fig.7 represented the relation between total GWP and mixing ratio of c-C_4F_8O which was obtained by the assumption of ideal gas condition. GWP for mixtures increased with mixing ratio of c-C_4F_8O raising from 1% to 100%. In addition, a phenomenon was put forward that GWP for c-C_4F_8O-N_2 mixtures was slightly higher than that of c-C_4F_8O-CO_2 mixtures attributing to a relatively low molecular mass of N_2. According to calculation results, GWP for c-C_4F_8O and N_2/CO_2 mixtures fell rapidly to about 5800 and 4800 as the proportion of c-C_4F_8O was less than 20%. If the mixing ratio consistently decreased, GWP for mixtures could reduce to 500, about one-fiftieth that of SF_6. The calculation results showed that mixing c-C_4F_8O with N_2/CO_2 could significantly reduce the GWP of gas mixture.

G. SELF-RECOVERY TEST OF c-C_4F_8O AND CO_2/N_2 MIXTURES
The self-recovery capability of insulating gas was also very important in the electric system. Therefore, self-recovery ability of c-C_4F_8O and its mixtures was studied. Each breakdown testing interval was two minutes and results were illustrated in Fig.8. In 50 times of breakdown tests, the testing values were always stable around the initial breakdown voltage, showing excellent self-recovery performance. The self-recovery capability of 20%c-C_4F_8O-80%N_2/CO_2 was also investigated. As shown in Fig.9, the breakdown voltage of 20%c-C_4F_8O-80%CO_2 was lower than that of 20%c-C_4F_8O-80%N_2. In addition, the dielectric strength of c-C_4F_8O-CO_2 gas mixture slightly decreased with the increase in breakdown numbers probably due to decomposition of c-C_4F_8O.
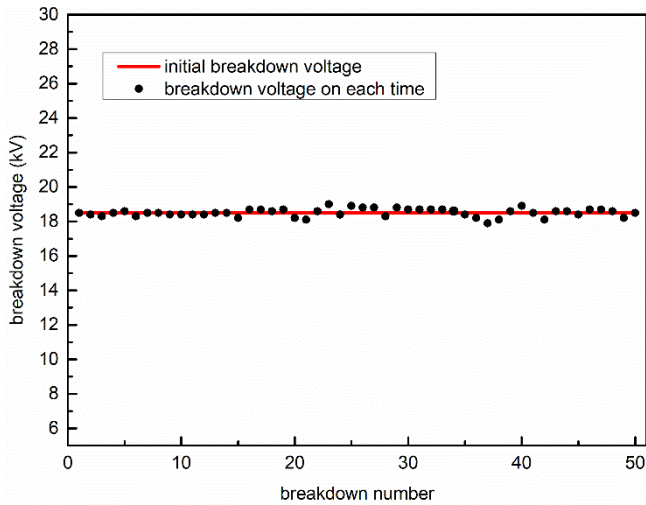
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Z. Gao *et al.*: Investigation of Synthesis and Dielectric Properties of c-C$_4$F$_8$O With Its CO$_2$/N$_2$ Mixtures as SF$_6$ Alternatives

FIGURE 8. c-C$_4$F$_8$O self-recovery testing results in quasi-uniform electric field at 0.1 MPa.

H. DECOMPOSITION MECHANISM OF c-C$_4$F$_8$O

The insulting medium in the equipment would decompose under flashover or partial discharge conditions to produce some by-products in the long-term use process. Therefore, clarifying decomposition products and studying decomposition mechanism of insulting medium were critical to the safety of equipment maintenance. Firstly, decomposition products of c-C$_4$F$_8$O after multiple breakdown tests were investigated by GC. Test conditions were as follows: the initial temperature was 30 °C and the temperature was held for 5 min, then was up to 110 °C at a rate of 20 °C/min. The final temperature was held for 2 min. Results of decomposition products were demonstrated by Fig.10. The GC showed that components of the c-C$_4$F$_8$O exhibited little change. In other words, the c-C$_4$F$_8$O didn't decompose after breakdown test. To further understand the decomposition mechanism of c-C$_4$F$_8$O, the gas phase radical decomposition reaction was calculated by Gaussian 09.

The decomposition process was indicated by Table 3 and reaction free energy of c-C$_4$F$_8$O with geometry of molecules was shown in Fig.11. c-C$_4$F$_8$O has a five-membered ring structure that might decompose to form radical structure by removing fluorine and oxygen atom as shown in Fig.11 *b* (C$_4$F$_7$O), *c* (C$_4$F$_7$O), *g* (C$_4$F$_8$) or bond cleavage between C-O and C-C could be occurred with diradical molecules *d* (C$_4$F$_8$O), *e* (C$_4$F$_8$O), *f* (C$_4$F$_8$O) formed. According to Table 3, the forming of 1, 2, 3 was even easier than that of 4, 5, 6 because of lower reaction free energy. It also indicated that *b*, *c*, *g*, were not main products. After ring-open reactions, diradical molecules *d*, *e*, *f*, were immediately decomposed into small stable molecules *h* (C$_2$F$_4$), *i* (c-C$_2$F$_4$O), *j* (c-C$_3$F$_6$)

(a)
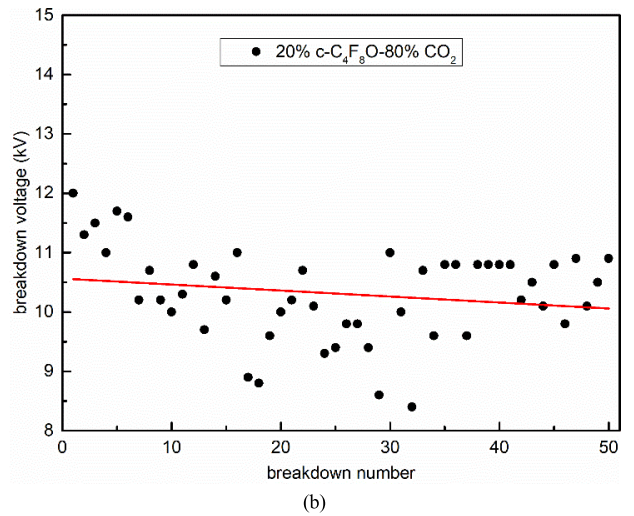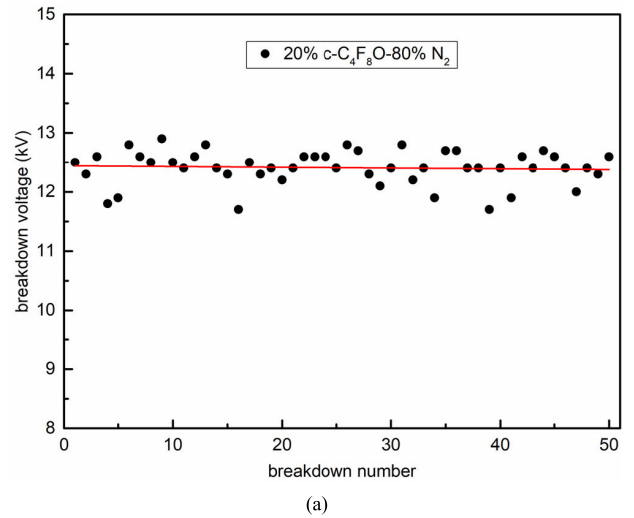

(b)

FIGURE 9. c-C$_4$F$_8$O-N$_2$/CO$_2$ mixtures self-recovery testing results in quasi-uniform electric field at 0. 1 MPa.
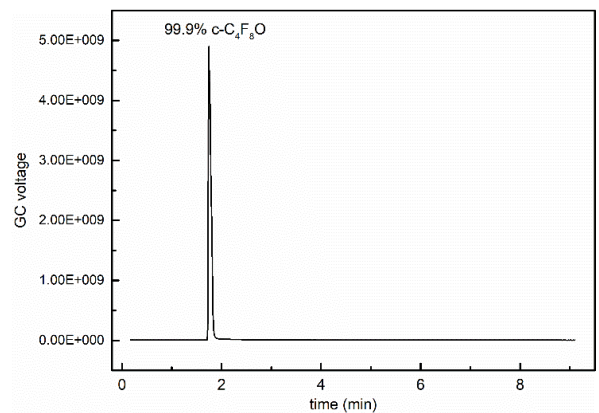

FIGURE 10. Gas chromatogram (GC) of decomposition products after c-C$_4$F$_8$O breakdown test.

and *k* (CF$_2$O) with the exothermic process. The total reaction free energies from *a* to *h*, *i* and *j*, *k* were 50.667 and 33.958 kcal/mol respectively.

Z. Gao *et al.*: Investigation of Synthesis and Dielectric Properties of c-C_4F_8O With Its CO_2/N_2 Mixtures as SF_6 Alternatives
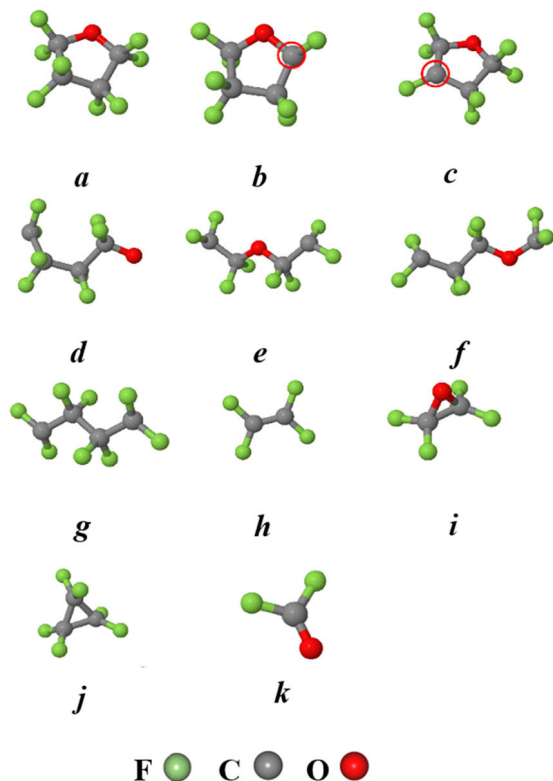
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FIGURE 11. Geometry structures of molecules after the optimization with B3LYP/6-31G(d,p).

TABLE 3. Decomposition mechanism and reaction free energy of c-C_4F_8O.

NO	Reaction	$E^a_{reactant}$(a.u.)	$E^b_{product}$(a.u.)	Reaction free energy(kcal/mol)^c
1	$a \rightarrow e$	-1026.330	-1026.209	76.286
2	$a \rightarrow f$	-1026.330	-1026.204	78.983
3	$a \rightarrow d$	-1026.330	-1026.192	86.733
4	$a \rightarrow b$ + F-ion	-1026.330	-1026.154	110.474
5	$a \rightarrow c$ + F-ion	-1026.330	-1026.165	103.594
6	$a \rightarrow g$ + O-*ion*	-1026.330	-1026.056	171.834
7	$d \rightarrow h + i$	-1026.191	-1026.249	-36.068
8	$d \rightarrow j + k$	-1026.191	-1026.276	-52.775
9	$e \rightarrow h + i$	-1026.209	-1026.249	-25.621
10	$f \rightarrow h + i$	-1026.204	-1026.249	-28.318
11	$f \rightarrow j + k$	-1026.204	-1026.276	-45.024

^{a} Energy of reactant; ^{b} Energy of product; ^{c} =($E_{product}$-$E_{reactant}$)* 627.51 kcal/mol

I. COMPREHENIVE ASSESSMENT

c-C_4F_8O was successfully synthesized after optimization with the yield of 55.7%. Parameters about preparation of c-C_4F_8O were compared in Table 4. Tetrahydrofuran and anhydrous hydrogen fluoride were used to prepare c-C_4F_8O under electrolysis with the yield of 42.2%. However, the electrolytic method had some weakness, such as more requirements on equipment, high toxicity of raw material and low yield. The fluorine cyclization was also a method of producing c-C_4F_8O. But extremely toxic fluorine was employed in this process. Finally, a novel technique was presented by

TABLE 4. Comparison of parameters about preparation of c-C_4F_8O.

Preparation	Reactants	Reaction conditions	Yield (%)
Electrolysis	Tetrahydrofuran; anhydrous hydrogen fluoride	electrolysis	42.2%
Fluorine Cyclization	Perfluoroglutaryl fluoride; fluorine; potassium fluoride	25 °C	-^{a}
Fuming sulphuric acid	Fuming sulphuric acid; 1,4-diiodoperfluorobutane	80 °C	55.7%

^{a} The yield was not reported

TABLE 5. Properties comparison between SF_6 and c-C_4F_8O.

Parameters	SF_6	c-C_4F_8O
Relative molecular mass	146.06	215.98
Boiling point/°C (0.1 MPa)	-63	0
GWP	23900	8700
ODP	0	0
Toxicity	non-toxic	low-toxic
Relative insulation strength	1.0	1.2~1.4
Decomposition products	SO_2, SO_2F_2, SOF_2, SOF_4, HF, S_2F_{10}	C_2F_4, c-C_2F_4O, c-C_3F_6, CF_2O

using fuming sulfuric acid and 1,4-diiodoperfluorobutane. This method had simple and convenient preparation process with lower requirement on equipment. The yield of c-C_4F_8O was also greatly improved after optimization.

Based on testing and analysis results, comparison of properties between SF_6 and c-C_4F_8O were made, as shown in Table 5. SF_6 was traditionally employed as insulating gas in virtue of preeminent dielectric properties, low liquefaction temperature and non-toxicity. However, high GWP of SF_6 limited its use in the electrical system. In addition, decomposition products of SF_6 were mainly highly toxic by-products, such as SO_2F_2, SOF_2, SOF_4, HF and S_2F_{10} [33], [34]. According to the Table 3, GWP of c-C_4F_8O was 8700, about one-third that of SF_6 with lower impact on the environment. The dielectric strength of c-C_4F_8O was 1.2-1.4 times that of SF_6 and decomposition by-products were mainly C_2F_4, c-C_2F_4O, c-C_3F_6 and CF_2O with good insulation properties. The results indicated that c-C_4F_8O had potential to replace SF_6 after a series of contrastive analysis.

V. CONCLUSION

In summary, c-C_4F_8O was successfully synthesized with the yield of 55.7% when the molar ratio of 1,4-diiodoperfluorobutane and fuming sulfuric acid of containing 50% SO_3 was 11:1 under 80 °C; Then, the breakdown voltage of c-C_4F_8O and its mixtures were tested with properties in environmental and physical aspects analyzed. The dielectric strength of pure c-C_4F_8O was 1.2-1.4 times that of SF_6 from 0.100 MPa to 0.225 MPa. The boiling

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Z. Gao *et al.*: Investigation of Synthesis and Dielectric Properties of c-C₄F₈O With Its CO₂/N₂ Mixtures as SF₆ Alternatives

point of c-C_4F_8O was about 0 °C in 0.100 MPa and it needed to be mixed with N_2 or CO_2 with the GWP decreased simultaneously. The insulation performance of c-C_4F_8O-N_2 mixtures was relatively higher than that of c-C_4F_8O-CO_2 mixtures. In addition, pure c-C_4F_8O and 20%c-C_4F_8O-80%N_2 gas mixtures all exhibited excellent self-recovery ability after 50 times of breakdown test. However, the breakdown voltage of 20%c-C_4F_8O-80%CO_2 dropped slightly. Finally, the decomposition mechanism of c-C_4F_8O was investigated by Gaussian 09 showing that it might produce some by-products in the process of decomposition, such as C_2F_4, c-C_2F_4O, c-C_3F_6 and CF_2O. After all the above factors having been considered, c-C_4F_8O-N_2 mixtures have potential to replace SF_6 in the electrical system and the mixing ratio of c-C_4F_8O should not exceed 20%.

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ZHANYANG GAO was born in Zhoukou, Henan, China, in 1993. He received the B.S. and M.S. degrees from the College of Chemistry and Molecular Sciences, Wuhan University, Hubei, in 2015 and 2018, respectively, where he is currently pursuing the Ph.D. degree. His research interests include research and development of environmentally-friendly insulating alternatives gas and designing economic chemical route.

Z. Gao *et al.*: Investigation of Synthesis and Dielectric Properties of c-C$_4$F$_8$O With Its CO$_2$/N$_2$ Mixtures as SF$_6$ Alternatives

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YI WANG was born in Huangshi, Hubei, China, in 1992. He received the B.S. degree from Huber Normal University, in 2015, and the M.S. degree from Wuhan University, Hubei, in 2017, where he is currently pursuing the Ph.D. degree. His research interests include research and development of environmentally-friendly insulating alternatives gas and designing economic chemical route.

WENJUN ZHOU was born in Hanchuan, Hubei, China, in 1959. He received the Ph.D. degree from the Wuhan University of Hydraulic and Electrical Engineering, in 1990. He is currently a Professor with the School of Electrical Engineering and Automation, Wuhan University, China. His research interests include high-voltage insulation and testing technology, lightning protection and grounding technology, and SF6 substitution technology.

SHIYAO WANG was born in Wuhan, Hubei, China, in 1995. He received the B.S. degree from the Wuhan Institute of Technology, Hubei, in 2017. He is currently pursuing the M.D. degree with Wuhan University, Hubei. His research interests include synthesis of environmentally-friendly insulating alternatives gas and process simulation of batch distillation.

PING YU was born in Shenzhen, Guangdong, China, in 1963. She received the Ph.D. degree from the Wuhan University of Hydraulic and Electrical Engineering, in 1999. She is currently a Professor with the College of Chemistry and Molecular Sciences, Wuhan University. Her research interests include water and wastewater treatment, metal corrosion and protection, membrane separation, and electrochemistry.

RUICHAO PENG was born in Qujing, Yunnan, China, in 1988. He received the Ph.D. degree from Wuhan University, China, in 2016. He currently holds a postdoctoral position at the College of Chemistry and Molecular Sciences, Wuhan University. His research interests include wastewater treatment and electrochemistry.

YUNBAI LUO was born in Xiantao, Hubei, China, in 1956. He received the B.S. degree in oil-refinery engineering from the East China Petroleum Institute, Shandong, in 1982, the M.S. degree in applied chemistry from the China University of Petroleum, Beijing, in 1988, and the Ph.D. degree in chemical engineering from Tianjin University, Tianjin, in 1999. He is currently a Professor with the College of Chemistry and Molecular Sciences, Wuhan University. He is mainly engaged in the research of electrochemistry and chemical separation.

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