IEEE Access
Multidisciplinary Rapid Review Open Access Journal

Received December 6, 2018, accepted January 7, 2019, date of publication February 5, 2019, date of current version February 22, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2897717

Thermal Compatibility Between Perfluoroisobutyronitrile-CO_2 Gas Mixture With Copper and Aluminum Switchgear

YI LI, XIAOXING ZHANG, JI ZHANG, QI CHEN, YALONG LI, SONG XIAO, ZHAOLUN CUI, AND JU TANG

School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China

Corresponding authors: Xiaoxing Zhang (xiaoxing.zhang@outlook.com) and Song Xiao (xiaosongxs@gmail.com)

This work was supported in part by the Science and Technology Project of China Southern Power Grid under Grant ZBKJXM20170090.

ABSTRACT Perfluoroisobutyronitrile (C_4F_7N) has received extensive attention over the past three years as an environmental friendly gas insulating medium. At present, there are few studies on the compatibility of C_4F_7N with metal materials used in the electrical equipment. In this paper, we constructed a gas–solid interfacial reaction platform and carried out aging tests for C_4F_7N-CO_2 gas mixture at different temperatures. The composition of the gas mixture and the surface morphology and the elemental composition of copper, aluminum were explored. The interaction mechanism between C_4F_7N-CO_2 gas mixture and metal surface was also analyzed. It was found that C_4F_7N-CO_2 gas mixture has better compatibility with aluminum than copper. The reaction between C_4F_7N-CO_2 gas mixture and heated copper at 220 °C produces the gaseous by-product C_3F_6. The surface color of copper deepens and the corrosive degree increases with temperature, while the interaction between C_4F_7N and heated aluminum does not cause gas decomposition and metal corrosion. In general, the thermal stability of C_4F_7N-CO_2 gas mixture associated with heated copper and aluminum is inferior to that of SF_6.

INDEX TERMS C_4F_7N-CO_2, thermal compatibility, copper, aluminum, SF_6 alternative gas.

I. INTRODUCTION

Sulphur hexafluoride (SF_6) is widely used in the electrical industry as insulating and switching medium for medium-voltage (MV) and high-voltage (HV) gas insulated switchgear (GIS) due to its excellent properties of high dielectric strength, nontoxicity, chemical inertness, broad operating temperatures range and exceptional arc quenching properties [1]–[3]. However, SF_6 has the global warming potential (GWP) of 23500 CO_2 equivalents and an atmospheric life span about 3200 years, making it the most potent greenhouse gas (GHG) [4], [5]. It is reported that the current equilibrium warming due to SF_6 is 0.004 °C, with a clear tendency to increase [6]. Moreover, electrical industry is the main consumer and emitter of SF_6 and the total mass of banked SF_6 worldwide in electrical equipment is in the order of magnitude of 10^5 tons [6]. Thus, much effort has been made across the industry over the last decades to find a viable alternative gas to SF_6.

The associate editor coordinating the review of this manuscript and approving it for publication was Bora Onat.

Recently, C_4F_7N (2,3,3,3-tetrafluoro-2-(trifluoromethyl)-2-propanenitrile, Perfluoroisobutyronitrile) has been listed as a potential substitute gas for SF_6. C_4F_7N has an exceptionally low GWP of 2090, the zero ozone depletion potential (ODP) and a dielectric withstand roughly twice as high as that of SF_6 [7], [8]. While its boiling point reaches to −4.7°C at normal pressure that can only be used as additive to a background gas such as CO_2, N_2 or technical air. Experimental and theoretical studies have been conducted on the dielectric strength [9]–[11], decomposition characteristics [12]–[15], switching behavior [16], [17] of C_4F_7N gas mixture over the past few years, confirming that C_4F_7N has potential using in HV gas insulated equipment (GIE).

In addition, the stability of alternative gases can be a key factor for the application in high voltage GIE which is typically designed for a life-time of 50 years and more with very few maintenance activities [18]. Therefore reliable data about the chemical long-term stability of gas insulating medium is required. Moreover, gas mixture is contacting with different materials in the GIE, such as metals, polymers and desiccants. Thus the interaction between the gas mixture and materials also need to be investigated and understand. And the aging principles on gas mixture as well as the materials in contact with it should be known to get a base for prediction of the lifetime of the equipment.

At present, there are few reports on the compatibility between C_4F_7N gas mixture and materials using in the equipment. Kessler *et al.* [19] investigated the gas-material interaction for C_4F_7N gas mixture and small quantities of decomposition products such as hexafluoro propene and heptafluoro propane were found when C_4F_7N contacted with desiccant for several weeks. Our team explored the interaction between C_4F_7N and Cu (1 1 1), Ag (1 1 1), Al (1 1 1) based on the density functional theory (DFT). We found that the adsorption of C_4F_7N on Cu (1 1 1) has higher adsorption energy and total charge transfer value than that of Ag (1 1 1) and Al (1 1 1) surface, indicating that the interaction between C_4F_7N and Cu (1 1 1) is stronger [20], [21].

In this paper, we carried out accelerated aging tests on C_4F_7N-CO_2 gas mixture interacting with copper, aluminum using in GIS as current-carrying conductors [22]. The composition of chemical elements and morphology of metal surface after aging tests were tested using the optical microscope, scanning electron microscope (SEM) and X-ray photoelectron spectroscopy (XPS). The gas composition of C_4F_7N gas mixture after tests was also detected and analyzed by gas chromatography-mass spectrometer (GC-MS). Relevant results not only revealed the thermal compatibility between C_4F_7N and copper, aluminum comprehensively, but also provide references for evaluating the lifetime of the equipment with C_4F_7N-CO_2 gas mixture.

II. METHOD

A. EXPERIMENTAL METHODS

In order to explore the interaction between C_4F_7N-CO_2 gas mixture and copper, aluminum, the aging test platform shown in Figure 1 was used. The test platform is mainly consist of the gas chamber, the temperature control system and the gas-solid interfacial reaction module. The gas chamber which can withstand the pressure of about 0.6MPa is made of 304L stainless steel. The pressure and temperature of the gas mixture in the chamber is monitored using the barometer and gas temperature sensor. We used the K-type temperature sensor to test the temperature of the heating element. The heating and temperature control system mainly includes the heating element, the switching power supply, the solid state relay, the proportion integration differentiation (PID) controller and interface temperature sensor components. The PID controller receives the signal of the interface temperature sensor and controls the switch power supply through solid state relay, so as to control on-off of the heating element and keep its temperature at a stable value. The gas-solid interfacial reaction module is made of copper or aluminum, which is used to simulate the current-carrying bus in the real electrical equipment.

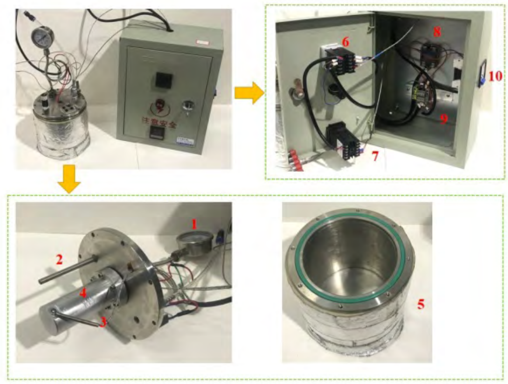


FIGURE 1. Structure of test platform: 1- barometer, 2- gas temperature sensor, 3- interface temperature sensor, 4- gas-solid interfacial reaction module, 5- gas chamber, 6,7 - temperature control and display module, 8,9 - solid state relay, 10- switch.

The inner wall of the gas chamber as well as the metal sheet and the gas-solid interfacial reaction module were cleaned before the test using the absolute alcohol and distilled water to remove the impurities. Then the gas-solid interfacial reaction module and the metal sheet with the size of 0.2∗5∗100mm are installed. The metal sheet fixed on the gas-solid interfacial reaction module can be used for sample characterization. The gas chamber was then pumped and filled with pure CO_2 gas (99.999%) to 0.3MPa, then pumped again to remove the gas impurities. This process is repeated for three times. Finally, the 10%C_4F_7N-90%CO_2 gas mixture was filled to the gas chamber to 0.3MPa to carry out relevant thermal aging tests at different temperatures.

Considering the requirement of pressure and liquefaction temperature for gas insulating medium in the equipment, the content of C_4F_7N in C_4F_7N-CO_2 gas mixture is generally less than 10% [23]. Therefore, we chooses 10%C_4F_7N-90%CO_2 gas mixture to carry out relevant tests. Moreover, the temperature of the current-carrying metal in the equipment under rated working condition is generally about 115-120°C. And the local overheating faults caused by poor contact of the breaker may lead to the temperature higher than the normal conditions. Thus we carried out relevant aging testes at 120°C, 170°C and 220°C to simulate the actual state of the current-carrying metals in the equipment under normal and overheating fault conditions. We carried out aging tests for C_4F_7N-CO_2 and copper at 220°C for several different period and found that the color of metal surface changed obviously after 40 hours interaction, indicating that this period is enough for reactions between gas mixture and copper to occur. Thus the test period was set to 40hours.

B. SAMPLE CHARACTERIZATION

The characterization of test samples includes gas composition analysis and metal characteristic analysis.

The GC-MS is used to detect components of C_4F_7N-CO_2 gas mixture before and after the test to determine whether some by-products are generated during the aging process.

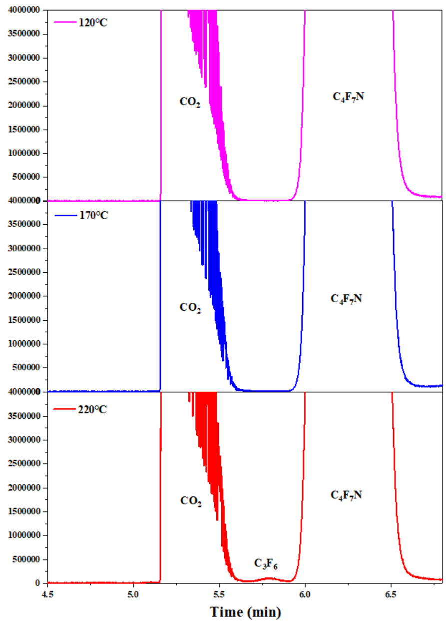


FIGURE 2. GC-MS spectra of C_4F_7N-CO_2 gas mixture after ageing tests.

The model of GC-MS and chromatographic column is Shimadzu Ultra 2010plus and CP-Sil 5CB (60m∗8um∗0.32mm), respectively. The working conditions of GC-MS are listed as follows: the temperature of the inlet and ion source is 200 °C, the split ratio is set to 10. The oven temperature is kept at 32°C for 10 minutes, and then heated up to 150°C with the increasing rate at 60°C/min.

In addition, the optical microscopy and field emission scanning electron microscopy (FESEM, Zeiss SIGMA) are used to characterize the morphology of the metal sheets for each group to reveal their morphological changes before and after the aging tests. The elemental composition of the metal surface is also investigated using the X-ray photoelectron spectroscopy (XPS).

III. RESULTS AND DISCUSSION

A. COMPATIBILITY BETWEEN C_4F_7N-CO_2 AND COPPER

1) GAS COMPONENTS

Figure 2 gives the gas chromatograms of C_4F_7N-CO_2 gas mixture after aging for 40 hours at different temperatures.

For the copper surface heated at 120°C and 170°C (The temperature of gas mixture at 69°C and 121 °C, respectively), there is no new characteristic peak appears in the gas chromatogram after the test, which indicates that the interaction process does not cause the decomposition of C_4F_7N-CO_2 gas mixture and the thermal stability of the gas mixture is great. When the temperature of gas-solid interface reached to 220 °C (The temperature of gas mixture reach 168°C), one decomposition by-product C_3F_6 can be found. Actually, it is reported that the thermal decomposition of C_4F_7N-CO_2 gas mixture starts at 650 and the first detected decomposition component is CO, while the other products such as COF_2, CF_3CN and C_2F_5CN are founded at 800°C [8]. While the temperature of gas mixture is lower than 200°C during the aging tests, which means the C_4F_7N-CO_2 gas mixture could not decomposition at this temperature. Therefore, C_4F_7N-CO_2 gas mixture is strongly interacted with copper at 220°C, causing the decomposition of C_4F_7N to generate C_3F_6.

On the whole, considering the temperature rise effect under normal working condition, C_4F_7N-CO_2 gas mixture exhibits excellent thermal stability with copper and the long-term interaction process do not cause the gas decomposition. While the high temperature (above 220°C) caused by the overheating faults will result in the decomposition of C_4F_7N-CO_2 gas mixture.

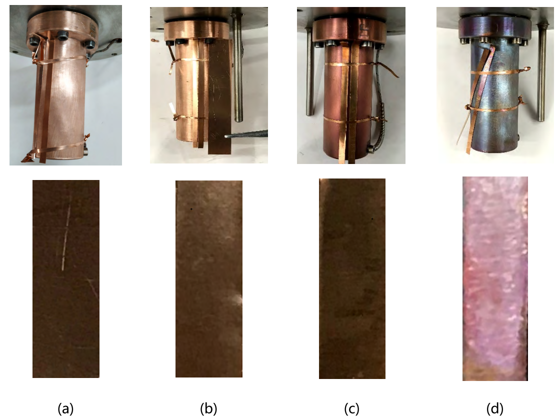


FIGURE 3. Photo images of copper surfaces before and after exposed to 10% C_4F_7N- 90%CO_2 environment for 40 hours: (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.

2) SURFACE MORPHOLOGY CHARACTERIZATION OF COPPER

Figure3 gives the photo images of copper surface before and after exposed to 10% C_4F_7N-90%CO_2 environment for 40 hours. It can be seen that the surface color of copper after 40 hours' interaction with C_4F_7N-CO_2 at 120°C is evenly distributed and has no significant difference with the untreated one. With the increase of the gas-solid interface temperature, the surface color of the copper exists some variations. The surface color changes from pale orange to dark orange after aging for 40 hours at 170°C, indicating that the copper has been corroded to a certain extent. When the temperature reaches to 220°C, the copper sheet becomes to fuchsia (purple) after interaction and the color distribution is uneven, which confirms that the copper has been seriously corroded at this condition.

Combined with the optical microscope images shown in Figure4, we can confirm that the copper begins to be corroded by 10%C_4F_7N-90%CO_2 at 170°C. Some surface area becomes to faint red at 170°C and the copper is deeply discolored when the temperature reaches to 220°C. The surface color turns into golden or fuchsia at this condition. Above all, the corrosion degree of copper is intensified with the

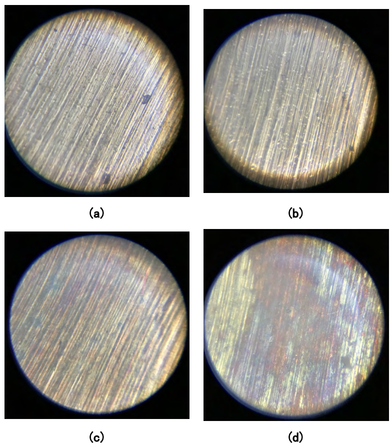


FIGURE 4. **Optical microscope images of copper surfaces before and after exposed to heated 10%C_4F_7N-90%CO_2 environment for 40 hours (Magnification: 200X): (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.**

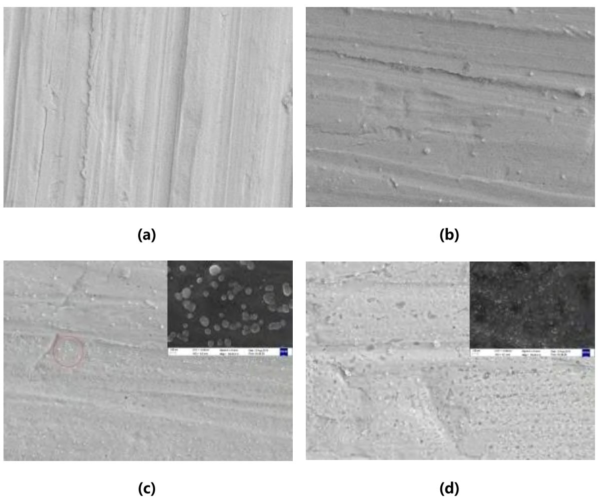


FIGURE 5. **SEM images of copper surfaces before and after exposed to 10%C_4F_7N-90%CO_2 environment for 40 hours (Magnification: 5K): (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.**

increase of interface temperature. The main characteristics of corrosion includes the deepening and uneven distributing of the surface color. Thus there exists incompatibility between C_4F_7N-CO_2 gas mixture and copper to a certain extent.

In order to further analyze the morphological modifications of the copper surface after the aging tests, all the samples were tested using the FESEM (as shown in Figure 5). We can find that the surface structure of untreated copper is flat and the cutting cross-section (in the form of thin texture) is clearly visible. A small amount of corrosion points which is randomly distributed can be found on the surface at 120°C. The structure of copper surface does not change significantly as a whole, indicating that the interaction between C_4F_7N-CO_2 gas mixture and copper does not destroy the microstructure of the metal surface. The distribution area and density of the corrosion points is increased with the interface temperature. Spherical or cube-like crystal particles can be found when the corrosion area is enlarged. The copper surface is basically covered by cube-like crystal particles when the temperature increases to 170°C, indicating that the microstructures of surface has been changed significantly. When the interface temperature reaches to 220°C, a large number of crystal particles produced are densely distributed in all areas of the copper surface. High magnification image shows that the particles are layered and the microstructure of copper surface is seriously damaged.

3) XPS ANALYSIS

Figure6 gives the XPS spectra of characteristics elements in copper surface before and after exposed to 10%C_4F_7N-90%CO_2 environment for 40 hours. All the XPS spectra were internally calibrated by adventitious carbon C1s binding energy at 284.8 eV and then fitted using the Gaussian method [24], [25]. Relevant chemical states analysis were finally carried out based on the National Institute of Standards and Technology (NIST) XPS database.

According to the high-resolution spectra of Cu2p shown in Figure 6 (a), there exists four main peaks locate at 932.46eV, 934.75eV, 952.33eV and 954.72eV, corresponding to the Cu $2p_{3/2}$, CuO $2p_{3/2}$, CuO$2p_{1/2}$ and Cu $2p_{1/2}$, respectively. The O1s spectra of the samples after aging tests can be described as two peaks by Gaussian distribution locating at 530.42eV and 531.84eV, which belongs to the C=O and CuO components. Therefore, the copper surface was oxidized after interacting with C_4F_7N-CO_2 gas mixture at 120°C-220°C for 40 hours.

The XPS spectra of C1s after aging tests at 120 °C is made up of two individual peaks at binding energies near 284.8 and 288.56eV, which are attributed to the C1s and COO components. As to the samples treated at 170°C and 220°C, the C1s peak at 293.53 eV can be found, which is associated with the C-F component. Moreover, the high-resolution spectra of F shows that the CF_x component located at 688.98eV can be seen for all groups after interaction. And the peaks centered around 684.69eV can be ascribed to CuF_2. Thus the interaction between copper and C_4F_7N-CO_2 gas mixture brings fluorine to the copper surface and generates CuF_2 at 170°C and 220°C.

As a whole, C_4F_7N-CO_2 gas mixture could react with copper at high temperature. The composition of the gas mixture did not change significantly at 120°C and 170°C, while the interaction between C_4F_7N-CO_2 gas mixture and copper at 220°C resulted in decomposition of gas mixture to produce some by-products such as C_3F_6. As the interface temperature increases, the color of the copper surface gradually deepens and its distribution becomes uneven. SEM results shows that a large number of crystalline particles are generated, and the corrosion of the surface is further aggravated. XPS results also show that the C_4F_7N-CO_2 gas mixture reacted with copper could produce CuO, CuF_2 and cause fluorine accumulation on the metal surface. Although the temperature rise effect under normal condition will not corrode copper or cause gas decomposition, the high temperature generated under overheating fault conditions will promote the interaction between C_4F_7N-CO_2 gas mixture and current-carrying

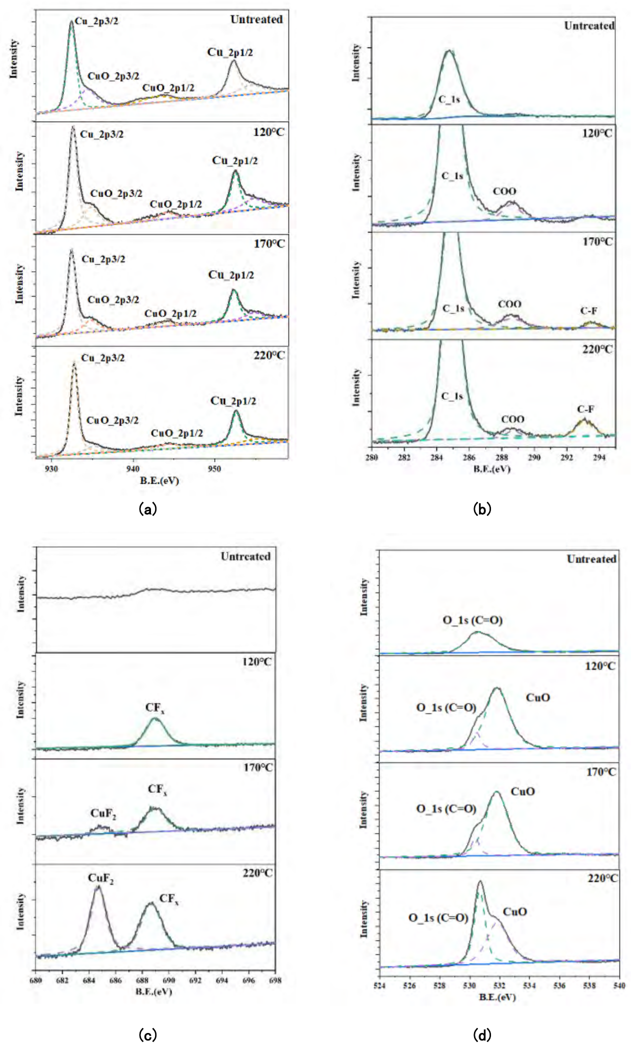


FIGURE 6. XPS spectra of characteristics elements in copper surfaces before and after exposed to 10%C_4F_7N-90%CO_2 environment for 40 hours: (a) Cu, (b) C, (c) F, (d) O.

copper, which will pose a certain threat on the service life of the equipment.

B. COMPATIBILITY BETWEEN C_4F_7N-CO_2 AND ALUMINUM

1) GAS COMPONENTS

Aging tests for aluminum and C_4F_7N-CO_2 gas mixture were also conducted at 120°C, 170°C and 220°C to investigate the compatibility between them. Figure 7 gives the GC-MS spectra of C_4F_7N-CO_2 gas mixture after ageing tests for 40hours. It can be seen that the C_4F_7N-CO_2 gas mixture does not generate any new characteristic peaks after interaction with the heated aluminum surfaces at 120°C, 170°C and 220°C (The temperature of gas mixture at 71°C, 122 °C, and 174°C, respectively), indicating that composition of the gas mixture does not change significantly, that is, the C_4F_7N-CO_2 gas mixture exhibits great compatibility with aluminum at 120°C-220°C.

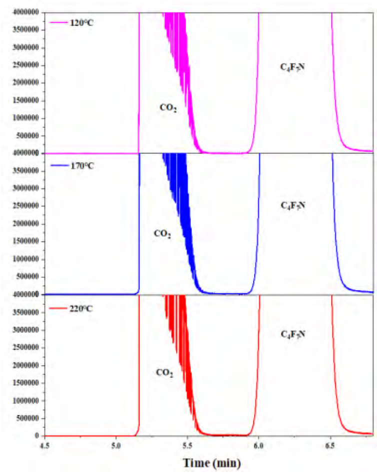


FIGURE 7. GC-MS spectra of C_4F_7N-CO_2 gas mixture after ageing tests.

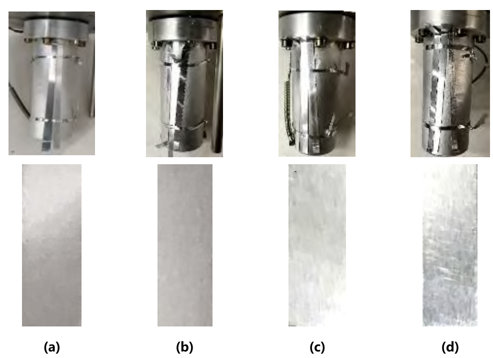


FIGURE 8. Photo images of aluminum surfaces before and after exposed to heated 10%C_4F_7N-90%CO_2 environment for 40 hours: (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.

2) SURFACE MORPHOLOGY CHARACTERIZATION OF ALUMINUM

Figure 8 gives the photo images of aluminum surfaces before and after exposed to 10%C_4F_7N-90%CO_2 for 40 hours. We can find that the aluminum surface before the test has a uniform color distribution. And the surface color does not change significantly after interacting with C_4F_7N-CO_2 gas mixture at different temperatures. Combining with the optical microscopy results shown in Figure 9, it can be seen that the texture of the aluminum is clear, and the surface structure is not corroded after the tests. Therefore, the interaction between C_4F_7N-CO_2 gas mixture and aluminum will not lead to significant changes in the surface structure of aluminum.

Figure 10 shows the SEM results of aluminum after the aging tests. It can be seen that the untreated aluminum has clear texture and flat structure. After interacted with C_4F_7N-CO_2 gas mixture, a small amount of particles are generated and randomly distributed on the aluminum surface. With the increase of surface temperature, the content of the above particles increased slightly. On the whole, C_4F_7N-CO_2 gas mixture did not cause serious corrosion to the aluminum, thus the compatibility between them is great.

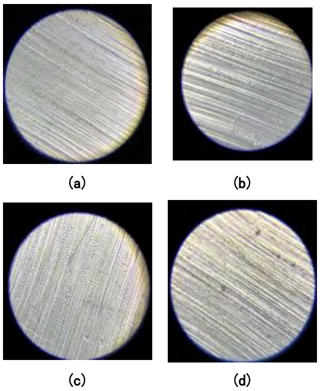


FIGURE 9. **Optical microscope images of aluminum surfaces before and after exposed to heated 10%C_4F_7N-90%CO_2 environment for 40 hours(Magnification: 200X): (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.**

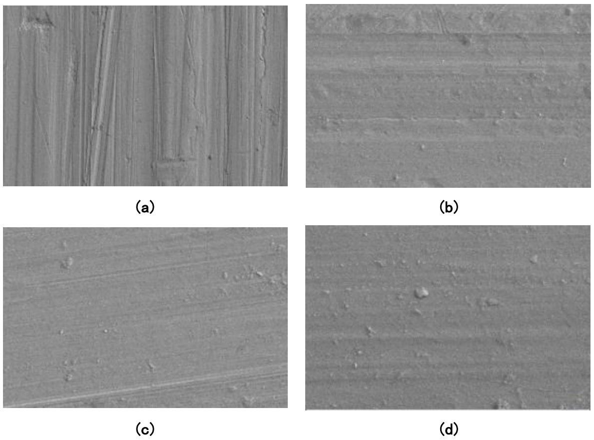


FIGURE 10. **SEM images of aluminum surfaces before and after exposed to heated 10%C_4F_7N-90%CO_2 environment for 40 hours (Magnification:5K): (a) Unheated, (b) 120°C, (c) 170°C, (d) 220°C.**

3) XPS ANALYSIS

XPS measurement is also carried out to further analyze the composition of the elements and surface chemical states in the samples. Figure 11 shows the XPS spectra of characteristics elements in aluminum surface before and after exposed to 10%C_4F_7N-90%CO_2 environment for 40 hours.

It can be found that the binding energies for Al2p are mainly located at 71.89eV and 74.37eV, which are attributed to Al and Al_2O_3, respectively. According to the high-resolution spectra of O1s, the binding energy at 531.79eV can be ascribed to Al_2O_3. The other peaks at 533.27eV can be found for the aging samples at 220 °C, corresponding to the COO component.

Figure 11 (b) and (c) presents the high resolution XPS spectra of C1s and F1s. Two peaks centered at 288.8eV and 284.92eV belong to the C1s and COO components, respectively. And another two peaks located at 285.94eV and 292.83eV are attributed to CN group and CF_x component, indicating the aging process introduced CN and CF_x to the metal surface. The high resolution XPS spectra of F1s also confirms the generation of fluorine on the metal surface after

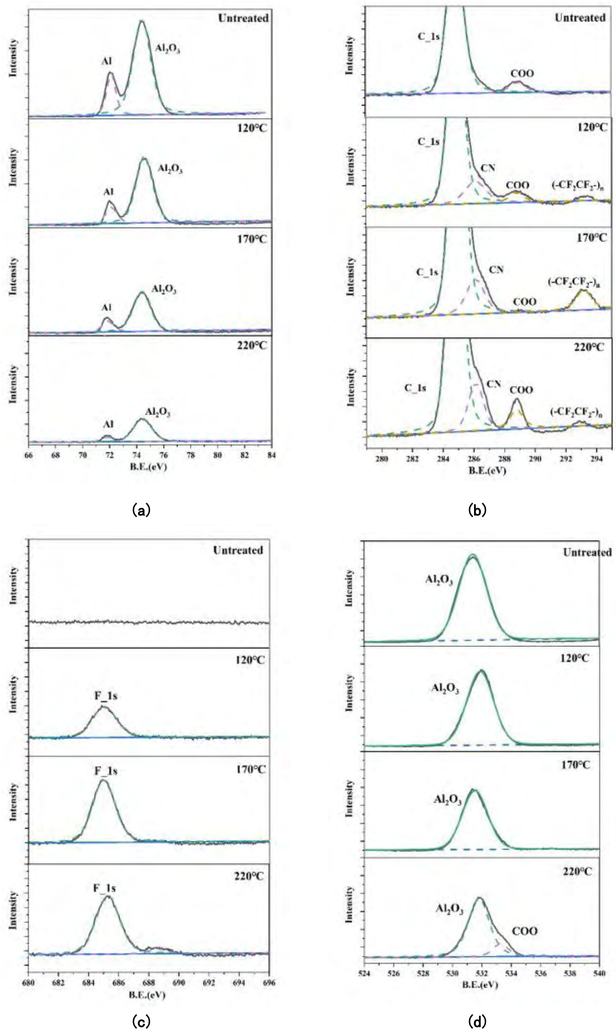


FIGURE 11. **XPS spectra of characteristics elements in aluminum surfaces before and after exposed to 10%C_4F_7N-90%CO_2 environment for 40 hours: (a) Al, (b) C, (c) F, (d) O.**

interaction and the peak located around 689.12eV at 220°C belongs to the CF_x components.

Therefore, the composition of the C_4F_7N-CO_2 gas mixture and the surface morphology of the aluminum does not change significantly after aging tests, but amount of fluorine accumulation occurs. On the whole, the compatibility of C_4F_7N-CO_2 gas mixture with aluminum is great. Considering several conditions such as temperature rise effect and potential overheating faults in real equipment, C_4F_7N-CO_2 gas mixture will not corrode the aluminum to a certain extent.

C. DISCUSSION

According to the test results, the compatibility of C_4F_7N-CO_2 gas mixture with copper is inferior to that of aluminum. The reaction between C_4F_7N-CO_2 gas mixture and copper at high temperature results in the decomposition of C_4F_7N-CO_2 gas mixture and corrosion of metal surface. At the same time, XPS results show that copper surface generates CuO, CuF_2 and other substances after interaction, while the interaction

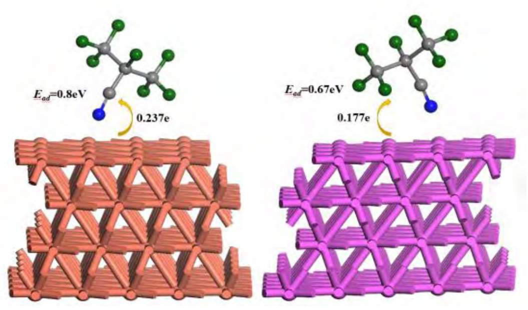


FIGURE 12. Interaction between C_4F_7N and Cu (1 1 1), Al (1 1 1).

between C_4F_7N-CO_2 gas mixture and aluminum does not lead to gas decomposition or metal corrosion.

Actually, our team has explored the interaction mechanism between C_4F_7N with copper and aluminum based on the DFT [21]. We optimized various initial interaction structures and found that the CN group in the C_4F_7N molecule had strong reactivity. The maximum adsorption energy of C_4F_7N absorbed on the Cu (1 1 1) surface reaches to 0.8eV, and the interaction process is accompanied by total charge transfer of 0.237e. While the maximum adsorption energy of C_4F_7N absorbed on the Al (1 1 1) surface is 0.67eV accompanied by charge transfer of 0.177e (As shown in Figure 12). Relevant theoretical calculation results show that the interaction between C_4F_7N and Cu (1 1 1) is stronger than that of Al (1 1 1), which is consistent with the experimental results in this paper.

The reaction mechanism of C_4F_7N with copper and aluminum surface is summarized as follows:

$$C_4F_7N + Cu \rightarrow CuCN + C_3F_7 \quad (1)$$
$$C_3F_7 \rightarrow F + C_3F_6 \quad (2)$$
$$Cu + 2F \rightarrow CuF_2 \quad (3)$$
$$Al + 3F \rightarrow AlF_3 \quad (4)$$

Moreover, literature [22] tested the thermal stability of SF_6 associated with heated copper and aluminum. It is pointed out that the interaction between SF_6 and copper at 300°C would not change the color and composition of copper surface. When the temperature reached to 330-385°C, the color of copper surface changed obviously, and some sulfur elements is accumulated. Thermal aging test results for SF_6 and aluminum shows that aluminum does not react with SF_6 gas for applied heating mantle temperatures up to 400°C. In fact, although aluminum is more active than copper, it is easy to oxidize and forming the dense Al_2O_3 film on the surface, preventing further corrosion of the aluminum.

Generally, the stability of C_4F_7N-CO_2 gas mixture associated with heated copper and aluminum is inferior to that of SF_6. C_4F_7N-CO_2 gas mixture could react with heated copper, which causes the decomposition of C_4F_7N and formation of some gaseous by-products, as well as copper corrosion. The above problems will have a negative impact on the service life of the equipment under long-term conditions. Therefore, the copper current-carrying conductor for electrical equipment using C_4F_7N-CO_2 gas mixture gas mixture as the insulating medium should do anti-corrosion treatment to ensure the safety and lifetime of the equipment.

IV. CONCLUSION

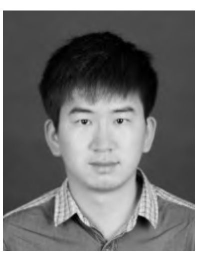
In this paper, the gas-solid interfacial reaction platform was constructed and the thermal aging tests of C_4F_7N-CO_2 gas mixture with copper, aluminum at different interface temperatures were carried out. The composition of C_4F_7N-CO_2 gas mixture as well as the surface structure and element composition of metal materials are explored and analyzed. The gas-solid interfacial mechanism is discussed and the compatibility of C_4F_7N-CO_2 gas mixture with copper and aluminum are evaluated. Several conclusions can be obtained as follows:

1) C_4F_7N-CO_2 gas mixture could react with copper at 220°C, resulting in the generation of C_3F_6 and strong corrosion on the metal surface. With the increase of interface temperature, the color of copper surface gradually deepens, and a large number of crystalline particles are produced. The generation of CuO, CuF_2 and fluorine accumulation on the metal surface can be found.
2) The interaction between C_4F_7N-CO_2 gas mixture and aluminum at high temperature will not lead to the decomposition of gas insulating medium and strong corrosion of aluminum surface. The morphology of aluminum does not change significantly and the compatibility between them is great.
3) The compatibility of C_4F_7N-CO_2 gas mixture with copper is weaker than that of aluminum, and the high temperature generated under overheating fault conditions will promote the interaction between gas mixture and copper, threatening the service life and safety of the equipment.
4) Anti-corrosion treatment is needed to prevent the corrosion of copper in subsequent engineering applications. Temperature monitoring is also suggested to be strengthened to avoid strong corrosion caused by overheating faults.

REFERENCES

[1] J. Tang *et al.*, "Investigation on SF_6 spark decomposition characteristics under different pressures," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2066–2075, Sep. 2017.
[2] X. Li, H. Zhao, and A. B. Murphy, "SF_6-alternative gases for application in gas-insulated switchgear," *J. Phys. D, Appl. Phys.*, vol. 51, no. 15, p. 153001, 2018.
[3] J. C. Devins, "Replacement gases for SF_6," *IEEE Trans. Electr. Insul.*, vol. 15, no. 2, pp. 81–86, Apr. 1980.
[4] J. Reilly *et al.*, "Multi-gas assessment of the Kyoto protocol," *Nature*, vol. 401, no. 6573, p. 549, 1999.
[5] R. Ullah, A. Rashid, A. Rashid, F. Khan, and A. Ali, "Dielectric characteristic of dichlorodifluoromethane (R12) gas and mixture with N_2/air as an alternative to SF_6 gas," *High Voltage*, vol. 2, no. 3, pp. 205–210, Sep. 2017.
[6] M. Rabie and C. M. Franck, "Assessment of eco-friendly gases for electrical insulation to replace the most potent industrial greenhouse gas SF_6," *Environ. Sci. Technol.*, vol. 52, no. 2, pp. 369–380, 2018.
[7] Y. Kieffel, T. Irwin, P. Ponchon, and J. Owens, "Green gas to replace SF_6 in electrical grids," *IEEE Power Energy Mag.*, vol. 14, no. 2, pp. 32–39, Mar. 2016.

[8] Y. Kieffel, "Characteristics of g^3—An alternative to SF_6," in *Proc. IEEE Int. Conf. Dielect. (ICD)*, vol. 2, Jul. 2016, pp. 880–884.
[9] A. Chachereau, A. Hösl, and C. M. Franck, "Electrical insulation properties of the perfluoronitrile C_4F_7N," *J. Phys. D, Appl. Phys.*, vol. 51, no. 49, 2018, Art. no. 495201.
[10] H. E. Nechml, A. Beroual, A. Girodet, and P. Vinson, "Effective ionization coefficients and limiting field strength of fluoronitriles-CO_2 mixtures," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 2, pp. 886–892, Apr. 2017.
[11] Y. Tu, Y. Cheng, C. Wang, X. Ai, F. Zhou, and G. Chen, "Insulation characteristics of fluoronitriles/CO_2 gas mixture under DC electric field," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1324–1331, Aug. 2018.
[12] X. Zhang, Y. Li, S. Xiao, S. Tian, Z. Deng, and J. Tang, "Theoretical study of the decomposition mechanism of environmentally friendly insulating medium C_3F_7CN in the presence of H_2O in a discharge," *J. Phys. D, Appl. Phys.*, vol. 50, no. 32, 2017, Art. no. 325201.
[13] Y. Li *et al.*, "Decomposition properties of C_4F_7N/N_2 gas mixture: An environmentally friendly gas to replace SF_6," *Ind. Eng. Chem. Res.*, vol. 57, no. 14, pp. 5173–5182, 2018.
[14] X. Zhang *et al.*, "Reactive molecular dynamics study of the decomposition mechanism of the environmentally friendly insulating medium C_3F_7CN," *RSC Adv.*, vol. 7, no. 80, pp. 50663–50671, 2017.
[15] M. Xu, J. Yan, Z. Liu, Y. Geng, and Z. Wang, "Simulation of the decomposition pathways and products of Perfluoronitrile C_4F_7N (3M:Novec 4710)," in *Proc. 4th Int. Conf. Electr. Power Equip. Switch. Technol. (ICEPE-ST)*, 2017, pp. 310–313.
[16] W. Chunlin, W. Yi, S. Hao, D. Jiawei, N. Chunping, and Y. Fei, "Thermophysical properties calculation of C_4F_7N/CO_2 mixture based on computational chemistry—A theoretical study of SF6 alternative," in *Proc. 4th Int. Conf. Electr. Power Equip. Switch. Technol. (ICEPE-ST)*, Oct. 2017, pp. 255–258.
[17] Y. Wu *et al.*, "Properties of C_4F_7N-CO_2 thermal plasmas: Thermodynamic properties, transport coefficients and emission coefficients," *J. Phys. D, Appl. Phys.*, vol. 51, no. 15, 2018, Art. no. 155206.
[18] B. Lutz, K. Juhre, M. Kuschel, and P. Glaubitz, "Behavior of gaseous dielectrics with low global warming potential considering partial discharges and electric arcing," in *Proc. CIGR Winnipeg Colloq.*, Winnipeg, MB, Canada. Sep./Oct. 2017.
[19] F. Kessler, W. Sarfert-Gast, M. Ise, and F. Goll, "Interaction of low global warming potential gaseous dielectrics with materials of gas-insulated systems," in *Proc. 20th Int. Symp. High Voltage Eng.*, Buenos Aires, Argentina, Aug./Sep. 2017.
[20] Y. Li, X. Zhang, S. Xiao, J. Zhang, D. Chen, and Z. Cui, "Insight into the compatibility between C_4F_7N and silver: Experiment and theory," *J. Phys. Chem. Solids*, vol. 126, pp. 105–111, Mar. 2019.
[21] X. Zhang *et al.*, "Dissociative adsorption of environment-friendly insulating medium C_3F_7CN on Cu(111) and Al(111) surface: A theoretical evaluation," *Appl. Surf. Sci.*, vol. 434, pp. 549–560, Mar. 2018.
[22] C. T. Dervos, P. Vassiliou, and J. A. Mergos, "Thermal stability of SF_6 associated with metallic conductors incorporated in gas insulated switchgear power substations," *J. Phys. D, Appl. Phys.*, vol. 40, no. 22, p. 6942, 2007.
[23] H. E. Nechmi, A. Beroual, A. Girodet, and P. Vinson, "Fluoronitriles/CO_2 gas mixture as promising substitute to SF_6 for insulation in high voltage applications," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2587–2593, Oct. 2016.
[24] M. Muniz-Miranda, F. Muniz-Miranda, and S. Caporali, "SERS and DFT study of copper surfaces coated with corrosion inhibitor," *Beilstein J. Nanotechnol.*, vol. 5, pp. 2489–2497, 2014.
[25] F. C. Correia *et al.*, "XPS analysis of ZnO:Ga films deposited by magnetron sputtering: Substrate bias effect," *Appl. Surf. Sci.*, vol. 458, pp. 1043–1049, Nov. 2018.



YI LI was born in Shangluo, Shanxi, China, in 1994. He received the bachelor's degree in electrical engineering from Wuhan University, Wuhan, China, where he is currently pursuing the Ph.D. degree with the School of Electric Engineering and Automation. His research interests include alternative gas of SF_6 and the fault diagnosis of high-voltage electrical insulation equipment.

XIAOXING ZHANG was born in Qianjiang, Hubei, China, in 1972. He received the bachelor's and master's degrees from the Hubei Institute of Technology and the Ph.D. degree from Chongqing University. He is currently a Professor with the School of Electric Engineering and Automation, Wuhan University. He is involved in the online monitoring and fault diagnosis of high-voltage electrical insulation equipment, the alternative gases of SF_6, the decomposition mechanism of insulating gas SF_6, and the new nano-sensor.

JI ZHANG was born in Dongying, Shandong, China, in 1990. He received the bachelor's degree in electrical engineering and automatic chemistry from Shandong Jianzhu University, China. He is currently pursuing the M.A. degree with the School of Electric Engineering and Automation, Wuhan University. His research interest includes SF_6 insulation gas replacement technology.

QI CHEN was born in Xiaogan, Hubei, China, in 1995. He is currently pursuing the M.A. degree with the School of Electric Engineering and Automation, Wuhan University. His research interest includes alternative gas of SF_6.

YALONG LI was born in Zhumadian, Henan, China, in 1989. He received the bachelor's degree in electrical engineering from Wuhan University, Wuhan, China, where he is currently pursuing the M.A. degree with the School of Electric Engineering and Automation. His research interests include SF_6 abatement technology and alternative gas of SF_6.

SONG XIAO was born in Zhangjiakou, Hebei, China, in 1988. He received the B.S. and Ph.D. degrees in electrical engineering from Chongqing University, Chongqing, China, and the Ph.D. degree in plasma engineering from the Université de Toulouse, Toulouse, France. He is currently an Associate Professor with the School of Electric Engineering and Automation, Wuhan University. His research interests include partial discharge online monitoring and gas substituting SF_6.

ZHAOLUN CUI was born in Binzhou, Shandong, China, in 1993. He received the bachelor's degree in electrical engineering from Wuhan University and Automation, Wuhan, China. He is currently pursuing the Ph.D. degree with the School of Electric Engineering, Wuhan University. His research interests include the decomposition mechanism of insulating gas SF_6 and gases spectrum detection technology.

JU TANG was born in Pengxi, Sichuan, China, in 1960. He received the B.Sc. degree from Xi'an Jiaotong University, Xi'an, China, and the M.Sc. and Ph.D. degrees from Chongqing University, Chongqing, China. He is currently a Professor with the School of Electrical Engineering and Automation, Wuhan University, and the Chief Scientist presiding over a National Basic Research Program of China (973 Program) (2009CB724506). At present, he is involved in high-voltage equipment online monitoring, fault diagnosis, signal processing, simulation analysis, and pattern recognition.