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Decomposition characteristics of $C_5F_{10}O$/air mixture as substitutes for SF_6 to reduce global warming

Yi Li[a], Xiaoxing Zhang[a,*], Song Xiao[a], Qi Chen[a], Dibo Wang[b]

[a] School of Electrical Engineering, Wuhan University, Wuhan 430072, China
[b] Electric Power Research Institute, China Southern Power Grid, Guangzhou 510623, China

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ABSTRACT

Sulfur hexafluoride (SF_6) is widely used in the power industry but is a serious greenhouse gas. Many researchers committed to achieving sustainable development of the power industry are finding alternatives to SF_6 gas. $C_5F_{10}O$ performs well in terms of environmental protection, insulation, and safety and is a potential environment-friendly alternative gas. In this paper, the insulation and decomposition characteristics of $C_5F_{10}O$/air gas mixture were examined using gas-insulation performance test platform, and decomposition products were detected by gas chromatography–mass spectrometry. The formation mechanism and distribution of $C_5F_{10}O$ decomposition products were analyzed through reactive molecular dynamics method and density functional theory. The influence of air on the decomposition of $C_5F_{10}O$ was also evaluated. Results showed that the decomposition of $C_5F_{10}O$/air gas mixture mainly produces $CF_3\cdot$, $C_3F_7\cdot$, $C_4F_7O\cdot$, CO, $CF_2\cdot$, $CF\cdot$, $F\cdot$ and CF_4. The breakdown voltage of $C_5F_{10}O$/air gas mixture decreased slightly after repeated breakdown tests, and CF_4, C_2F_6, C_3F_8, C_3F_6, C_4F_{10}, CF_2O were detected. These results can serve as a reference for the systematic comprehension of the decomposition characteristics of $C_5F_{10}O$/air gas mixture and for related engineering applications.

1. Introduction

Sulfur hexafluoride (SF_6) gas has excellent insulation and arc performance and has been widely used in the power industry. According to statistics, about 80% SF_6 in the world is used in various types of gas-insulated equipment in the power industry, such as high-voltage circuit breakers, gas-insulated lines (GIL) and so on [1]. However, SF_6 is a serious greenhouse gas, with its lifespan in the atmosphere exceeding 3200 years and greenhouse effect potential (GWP) that is 23,500 times that of CO_2 [2–4].The Kyoto Protocol explicitly listed SF_6 as one of the six restricted greenhouse gases in 1997 [5]. Over the past five years, SF_6 gas has grown in the atmosphere by 20%, and the constantly increasing greenhouse gas emissions will lead to an increase in global average temperatures of about 4 °C (Celsius degree) in 2100 [6,7]. In order to realize the coordinated and sustainable development of the power industry, and gradually eliminate the dependence on SF_6, searching for an environment-friendly SF_6 alternative gas as an insulating medium used in electrical equipment is of great urgency.

In the past two years, $C_5F_{10}O$ and its gas mixture have attracted attention in the field of alternative gas research. Its molecular structure is shown in Fig. 1. The GWP value of $C_5F_{10}O$ is only 1, and its ozone depression potential index (ODP) is 0. Although $C_5F_{10}O$ has a liquefaction temperature of up to 26.9 °C [8], its insulation performance is excellent with a dielectric strength twice than that of SF_6; thus it has the potential of reaching the insulation strength of SF_6 at the same atmospheric pressure by mixing with a low liquefaction temperature buffer gas such as CO_2, N_2, and air. Moreover, $C_5F_{10}O$ is nontoxic and has an occupational exposure limit time average of 225 ppm_v (parts per million). [8]. Therefore, $C_5F_{10}O$ has great properties in terms of environmental protection, insulation, and safety.

Several scholars tested the insulation performance of $C_5F_{10}O$ and its mixtures and found that $C_5F_{10}O$/air gas mixture has excellent insulation properties, and has potential use in medium-voltage and high-voltage electrical equipment [8–10]. For engineering applications, Asea Brown Boveri Ltd. (ABB) has developed a switch cabinet with $C_5F_{10}O$/air gas mixture as insulation medium. It has passed the relevant standard test of the International Electrotechnical Commission (IEC) and has been carried out in test run successfully [8].

To evaluate the performance of gas-insulated medium comprehensively, besides the insulation and arc extinguishing characteristics, the decomposition characteristics also need to be investigated. In long-term operations or fault conditions, the internal insulation defects of the equipment caused by aging will lead to partial discharge (PD) or flashover, resulting in the decomposition of gas insulation medium. For

* Corresponding author at: School of Electrical Engineering, Wuhan University, BaYi Street No.299, Wuhan, Hubei Province, China.
E-mail address: xiaoxing.zhang@outlook.com (X. Zhang).

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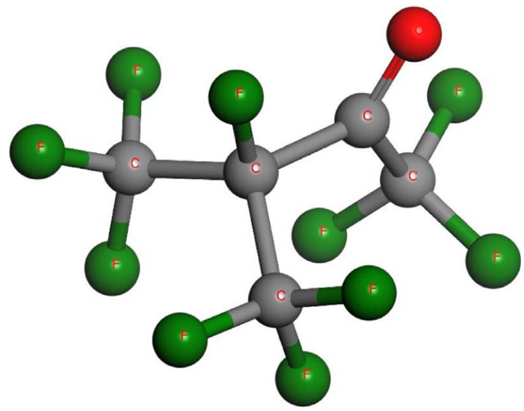

Fig. 1. Molecule structure of $C_5F_{10}O$.

example, the most widely used insulation medium, SF_6 can decompose and produce SO_2F_2, SO_2, SOF_2, and many other products [11]. The decomposition properties of gas insulating medium are closely related to its self-recovery characteristics, and the types of decomposition components also determine its safety. Therefore, the study of the decomposition characteristics of a new insulating medium needs to be done first, before engineering application.

At present, research on the decomposition characteristics of $C_5F_{10}O$ and its gas mixture have made some progress. Tatarinov et al. tested the decomposition of $C_5F_{10}O/N_2$ and $C_5F_{10}O$/air mixtures using dielectric barrier discharge (DBD) and found that the main products are C_4F_{10}, C_6F_{14}, C_5F_{12}, C_3F_6, and C_3F_8; and with the increase in applied voltage, the decomposition rate of $C_5F_{10}O$ increases. The decomposition rate of $C_5F_{10}O/N_2$ gas mixture is slower than that of $C_5F_{10}O$/air gas mixture at the same condition [12,13]. Hyrenbach et al. detected the composition of $C_5F_{10}O$/air gas mixture used in the switch cabinet as the insulating medium under long-term operation and internal arc faults by gas chromatography-mass spectrometry (GC–MS). Apparently, C_3F_7H and C_3F_6 are the main decomposition products under normal operating conditions. The components of CO, CO_2, CF_4, C_3F_8, and C_2F_6 are detected under internal arc tests [14]. Our team has calculated the possible decomposition paths of $C_5F_{10}O$ from the theoretical level and the effects of trace water were evaluated. The reaction enthalpy of each possible path, the ionization characteristics and toxicity of the decomposition products were analyzed [15,16]. We also studied the decomposition characteristics of $C_5F_{10}O/CO_2$ gas mixture and found that the main decomposition species are CF_3·and CO [17].

In this paper, the insulation and decomposition characteristics of $C_5F_{10}O$/air gas mixture were first tested using gas-insulation performance test platform and GC-MS. The decomposition mechanism of $C_5F_{10}O$/air gas mixture were theoretically explored by reactive molecular dynamics method (ReaxFF-MD) and density functional theory (DFT). The main decomposition paths and the influence of temperature on the reaction enthalpy were analyzed. Related research results provide a reference for a systematic and comprehensive understanding of the decomposition characteristics of $C_5F_{10}O$/air gas mixture and for related engineering applications.

2. Methods

2.1. Experimental method

The gas insulating performance test platform was used to conduct multiple breakdown tests on the $C_5F_{10}O$/air gas mixture, and the decomposition products were detected by GC-MS.

Fig. 2 shows the wiring diagram of the test system. The system consists of test transformers, protection resistors, capacitive voltage divider, and gas chamber. The transformer is used to provide high voltage; and the protective resistor is used to protect the test transformer, and to avoid the damage of the test transformer after overcurrent due to the breakdown. The capacitive divider is used to measure the actual voltage across the electrodes. The volume of the test chamber is 20 L; the main constituent material is 304 L stainless steel and polytetrafluoroethylene with excellent corrosion resistance, to avoid the chemical reaction between $C_5F_{10}O$ and gas chamber materials, and to ensure the accuracy of the composition test results.

The ball electrode, with radius of 25 mm and electrode interval of 5mm, was used to simulate a slightly non-uniform electric field. The electrode material is red copper. The electric field utilization coefficient is used to describe the electric fields with different uniformities, which is defined as $f = E_{av}/Emax$, where $Emax$ is the maximum electric field intensity, and E_{av} is the average electric field intensity [16]. The electric field utilization coefficient f of the ball electrode is 0.5168, hence, the electric field distribution between the ball electrode models is a slightly non-uniform electric field.

Before the test, the air tightness of the chamber was checked, and nitrogen was used to the wash the gas three times to eliminate the influence of the impurity in the air chamber. A mixture of 13.6% $C_5F_{10}O$, 69.12% N_2, and 17.28% O_2 is then added to 0.15 Mpa [14]. Then, the step-stress test (boost rate of about 0.5 kV/s) is used by applying the AC voltage to the positive and negative electrodes of the chamber until breakdown, and the instantaneous value of the breakdown voltage is recorded. The above test was repeated 30 times with an interval of 2 min. At the end of the test, the gas in the chamber was collected, and the gas components were tested by gas chromatography mass

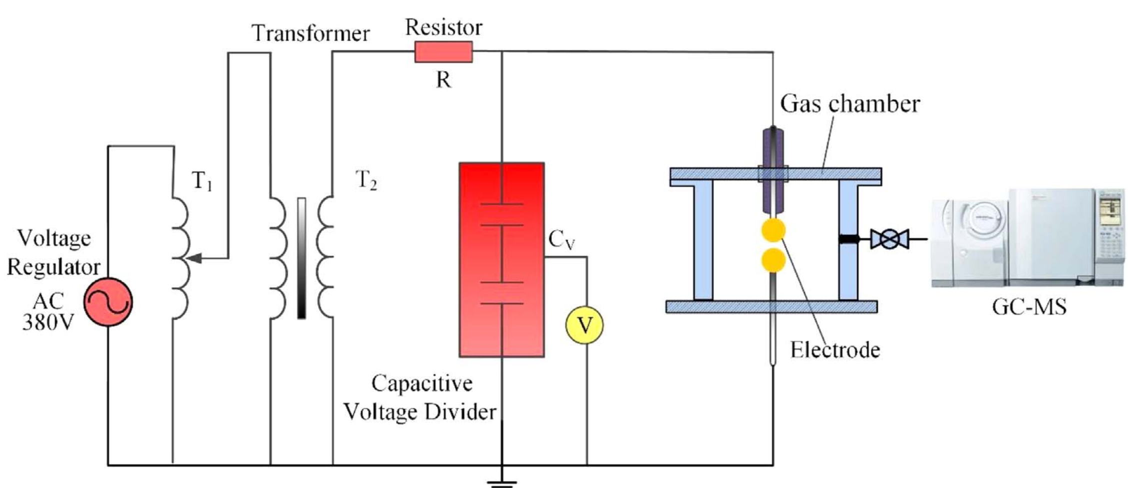

Fig. 2. Experimental system diagram.