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Research on Key Technologies for Measuring the Recovery Rate and Gas Measurement of SF_6 Gas On-site Maintenance Surface

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Abstract. Carrying out full lifecycle management of SF_6 gas recovery, purification, and recycling, developing new digital control technologies, and eliminating SF_6 gas emissions from the source are of great significance for achieving the "dual carbon" goal. Given the low level of digital control of SF_6 gas at present, especially in the situation, the SF_6 gas recovery rate, the effective volume of the gas chamber, and gas weight cannot be accurately measured at an on-site inspection surface, this paper carries out research on SF_6 gas recovery rate measurement at on-site inspection surface and key technologies of gas measurement. An intelligent online monitoring device such as SF_6 gas recovery rate and effective chamber volume of high voltage electrical equipment was developed, which can quickly identify SF_6 gas density, recovery rate, effective chamber volume, weight, and other parameters in high voltage electrical equipment, and evaluate the detection methods such as gas recovery rate and effective chamber volume. The results show that when the recovery rate was about 96.5%, the maximum positive deviation between the recovery rate measured by the detection device and that measured by the weighing method was 0.32% and the maximum negative deviation was -0.24%, both of which are less than 0.50%. When the container to be tested was 1000 L, the maximum indication error was -1.51%, which can meet the requirements of digital control in the SF_6 gas recycling and reuse process of high-voltage electrical equipment.

1. Introduction

SF_6 gas was a kind of strongly electronegative gas, and its molecules have a strong ability to absorb free electrons to form negative ions, so its resistance was very high. In a more uniform electric field, the electric field intensity of SF_6 gas was about 2.5 times that of air. It was the most ideal insulation and arc extinguishing medium at present. However, in the Kyoto Protocol, SF_6 gas was listed as one of the six greenhouse gases with limited emissions, and it was prohibited to discharge [1-3]. The physicochemical properties and application status of SF_6 gas were discussed. On the one hand, new technologies such as SF_6 gas recovery and purification, recharge, and life cycle management are vigorously developed at home and abroad to prevent leakage and emission from the source [4-6]. On the other hand, looking for a new type of insulating gas with excellent environmental protection and electrical properties can fundamentally solve the environmental problems of SF_6 [7]. Although domestic and foreign researchers have done a lot of research on the insulation properties and decomposition characteristics of new environmentally friendly insulating gases 2, 3, 3, 3-4 fluoro-2- (3 fluoromethyl) - propanitrile (4710) and 1, 1, 1, 3, 4, 4-7 fluoro-3- (3 fluoromethyl) -2-butanone (5110) [8-11], the timing of the large-scale application of replacement SF_6 gas was not yet known. From the technical and economic point of view, it was still not as good as SF_6 gas and can not completely replace SF_6 as an insulating medium. SF_6 gas was still the preferred insulating medium for high-voltage electrical equipment [12].

To reduce the consumption and emissions of SF_6 gas, respond to the national call for "carbon peaking and carbon neutrality", and deeply promote the green and low-carbon development of the power grid, the power industry has begun to use SF_6/N_2 mixed gas for promotion and application in electrical equipment. The application and promotion of SF_6/N_2 mixed gas in GIS can effectively reduce the application of SF_6 gas in power equipment. However, the use of mixed gases can not fundamentally solve the greenhouse effect problem caused by SF_6 gas emissions. With the improvement of social awareness of energy conservation and environmental protection and the progress of management and technology, SF_6 gas recovery and purification, recycling, and life cycle management

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technology are the most effective and feasible methods to control SF_6 gas consumption and emissions.

In 2019, the Ministry of Ecology and Environment required the SF_6 gas recovery rate to reach 96.5% in 2021, an increase of 1.5 percentage points over 2018 in the "Responsibility Letter for the Business Performance of the Head of the Central Enterprise". Based on the change in national policy, SF_6 gas has rapidly changed from independent emission reduction to mandatory emission reduction. It faced more severe challenges in the aspects of potential mining and control of SF_6 gas emission reduction. These include the lack and low level of digital controls. In particular, the SF_6 gas recovery rate, the effective volume of the gas chamber, and the weight of the gas can not be accurately measured on the on-site inspection surface, and there was still a certain gap with the relevant carbon emission regulatory requirements.

To solve the technical problems existing in the recycling process of SF_6 gas circulation for high-voltage electrical equipment, this paper studies the key technologies of SF_6 gas recovery rate measurement and gas metering on-site maintenance surface. An intelligent online monitoring device such as SF_6 gas recovery rate and effective volume of a gas chamber for high voltage electrical equipment has been developed. It can quickly identify SF_6 gas density, recovery rate, the effective volume of the gas chamber, weight, and other parameters in high-voltage electrical equipment. It can evaluate the detection methods such as gas recovery rate and effective volume of gas chamber, and provide important data support for SF_6 gas life cycle management.

2. Measurement principle

2.1. Gas recovery, density, and mass

To achieve a certain insulation capacity, the rated pressure of SF_6 gas in the air chamber of high-voltage electrical equipment was generally not less than 0.5 MPa. SF_6 gas in the gas chamber of high-voltage electrical equipment does not have the conditions of the ideal gas, and its state parameters cannot be determined by Charles' Law. In this paper, based on the Beattie-Bridgman equation of state [13-14], the state parameters before and after SF_6 gas recovery are calculated as shown in Equation (1), and then the inversion model of SF_6 gas recovery rate was derived.

$$P = (RTB - A)d^2 + RTd \tag{1}$$

where P was the absolute pressure (MPa) of SF_6 gas in the high-pressure switching gas chamber; T was the pressure (K) of the gas chamber, and d was the gas density of the SF_6 gas chamber (kg/m^3); A, B, and R are the constants measured by experiment, A=73.882×10^{-5}-5.132×10^{-7}d, B=2.50695×10^{-3}-2.12283×10^{-6}d, R=5.69502×10^{-4}.

The pressure P_1 and P_2, temperature T_1 and T_2 in the high-pressure switching gas chamber before and after recovery are measured by the high-precision pressure sensor and temperature sensor. According to Equation (1), given the state parameters P and T in the high-pressure switching gas chamber, the SF_6 gas densities d_1 and d_2 can be calculated. The volume V of the air chamber remains unchanged before and after recovery. If the volume V_1 of the irregular high-voltage switching gas chamber was known, the mass m_1 and m_2 (kg) of SF_6 gas in the high-voltage electrical equipment before and after recovery are shown in Equations (2) and (3), respectively.

$$m_1 = d_1 \times V_1 \tag{2}$$

$$m_2 = d_2 \times V_1 \tag{3}$$

where d_1 and d_2 are the density of SF_6 gas in the gas chamber before and after recovery, respectively. The recovery rate η (%) of SF_6 gas is shown in Equation (4).

$$\eta = \frac{\mathrm{m}_1 - m_2}{m_2} \times 100\% = \frac{d_1 - d_2}{d_1} \times 100\% = f(P,T) \tag{4}$$

It can be seen that in the SF_6 gas recycling process, the gas mass m and recovery rate in the gas chamber are both state functions of the gas chamber pressure P and temperature T. By measuring the pressure P and temperature T of the gas chamber before and after recovery, the mass and recovery rate of SF_6 gas recycling process can be retrieved.

2.2. Theoretical model of effective volume measurement of high-pressure switching gas chamber

In the process of SF_6 gas recycling, the measurement of SF_6 gas quality on the field inspection surface was of great significance for the realization of gas recycling and digital control. It can be seen from Equations (2) and (3) that the monitoring of SF_6 gas quality was closely related to the effective volume of the gas chamber of high-voltage electrical equipment. Therefore, the measurement of the effective volume of high-voltage electrical equipment becomes a key factor. When the pressure was high, the density of the gas increases, the distance between the molecules decreases, and the interaction of the molecules and their volume cannot be ignored. According to the equation of the state of SF_6 under actual gas behavior, the effective volume of an irregular typical device or model can be derived by introducing the "compression factor" (Z).

$$PV = nRTZ \tag{5}$$

where P was SF_6 gas pressure (Pa), V was the volume of the gas chamber (m^3), n was the amount of matter (mol), and R was the molar gas constant (J/(mol·k)). To obtain the effective volume of an irregular typical device or model, the volume model of the high-pressure switching gas chamber as shown in Figure 1 was established. In Figure 1, V_1 was the volume of the air chamber of the high-pressure electrical equipment and P_1 was the initial pressure of SF_6 gas in the gas chamber to be measured. We use a standard container whose volume was V_2 and vacuum the container, connect the two containers through the pipeline, then open the valve, let the pressure

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of the two containers balance, and record the balanced pressure P_2. The effective volume of the gas chamber of the high-voltage electrical equipment obtained was shown in Equations (6) and (7).

$$V_1 \times P_1 = (V_1 + V_2) \times P_2 \tag{6}$$

$$V_1 = P_2 V_2 / (P_1 - P_2) \tag{7}$$

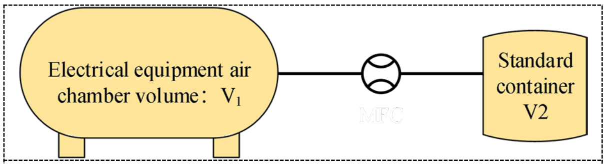

Figure 1. Measurement model of the effective volume of the air chamber

According to the above algorithm, the corresponding standard vessel was designed, and the pressure sensor with a measuring range of -0.1 MPa~0.9 MPa and an error of ±0.1% was selected. The pressure difference between the balanced pressure P_2 and the initial pressure P_1 of the air chamber to be measured was not greater than ΔP. It is ensured that the pressure drop of the air chamber during the measurement process does not influence the working state and the validity of the data. When P_1-P_2=ΔP, Equation (8) can be obtained from Equations (6) and (7).

$$V_2 = V_1 / (P_1 / \Delta P - 1) \tag{8}$$

The volume V_2 of the standard container can be retrieved from Equation (8) as shown in Figure 2. When ΔP=10 kPa, the size of the required standard container V_2 can be calculated by Equation (8). The volume of high pressure switching chamber varies. Relevant statistics show that the volume of gas chambers less than 5 m^3 accounts for about 89.45% of the total, and the design of the above standard container volume meets the application requirements. In the process of application, the multi-valve connection was adopted. According to the volume of different gas chambers to be measured, the corresponding standard container was selected directionally.

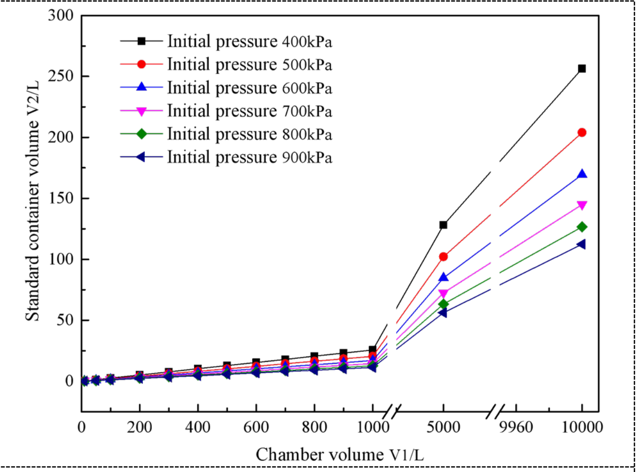

Figure 2. Standard container volume corresponding to a certain SF$_6$ chamber volume and initial pressure

3. Development of testing device

The design diagram of the detection system was shown in Figure 3. The device was connected to the SF$_6$ gas chamber of the high voltage electrical equipment through the intake pipe and was connected to the pressure sensing unit, temperature sensing unit, standard container, and SF$_6$ recovery device respectively after output by the stop valve and pressure regulator valve. The pressure sensing unit and the temperature sensing unit sense the pressure and temperature of SF$_6$ gas before and after recycling. Combined with the standard vessel, the data processing module based on the Beattie-Bridgman equation of state was used to measure the volume, density, mass, and recovery rate of SF$_6$ gas in high-voltage electrical equipment under certain temperature and pressure conditions, through the human-computer interaction interface for real-time display, and through Bluetooth, wifi, or LoRa to achieve wireless data transmission.

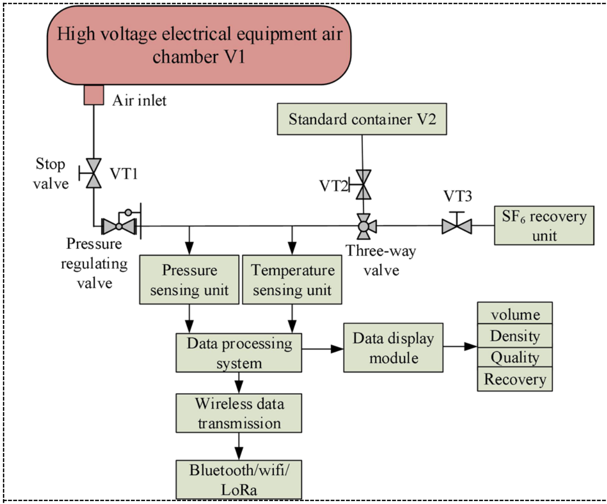

Figure 3. Design diagram of system detection module

4. Performance verification

4.1. Verification of SF6 gas recovery rates

To verify the recovery rate of the SF$_6$ gas recycling multi-parameter intelligent detection device, an electronic scale with a measuring range of 30 kg and an index value of 0.5 g was selected as a weighing instrument. An 8 L standard cylinder was used as an on-site SF$_6$-filled gas chamber container for recovery verification as shown in Figure 4. The mass of SF$_6$ gas filled with 600 kPa in the cylinder was about 300 g, and the accuracy of the electronic scale was about 0.167%. The mass of 1000 kPa gas was about 500 g, and the accuracy of the electronic scale was about 0.1%. All of the above meet the accuracy requirements of the recovery rate verification. The experimental design and procedures are as follows:

(1) After the equipment is ready, the 8 L standard steel cylinder was vacuumed with a two-stage rotary

vane vacuum pump (TRIVACD63L) until the absolute pressure was below 3 Pa, and the quality of the evacuated steel cylinder was accurately recorded by an electronic scale as m_1.

(2) We connect the inflation pipeline, SF_6 gas metering detection module, and SF_6 gas storage tank. Before inflation, the pressure-reducing valve of the standard steel cylinder is closed, and the pipeline system is vacuumed by the vacuum pump until the absolute pressure is below 3 Pa. We fill SF_6 gas to the absolute pressure of 400 kPa, 600 kPa, 800 kPa, and 1000 kPa respectively. Then we remove the gas line and metering module and rest for 3 hours and record the temperature t_1 of the standard cylinder at different pressures and the corresponding SF_6 gas cylinder mass m_2 accurately.

(3) We connect the recovery pipeline, SF_6 gas measurement and detection module, and SF_6 gas recovery device and conduct recovery operations on SF_6 gas separately. During the operation, we check the gas recovery rate displayed in the SF_6 gas measurement and detection module. When the recovery rate reaches around 96.5%, we stop the recovery, end the measurement, and close the recovery pipeline.

(4) Where the temperature t_2, pressure P_2, cylinder mass m_3, and gas recovery rate η_1 in SF_6 gas measurement and detection module corresponding to the standard cylinder after recovery were recorded at different filling pressures.

(5) According to the quality of the standard cylinder before and after recovery, the mass recovery rate η_2 was calculated, as shown in Equation (9).

$$\eta_2 = \frac{m_2 - m_3}{m_2 - m_1} \times 100\% \tag{9}$$

(6) According to the above experimental procedures, repeated sampling was performed, and the experimental data were shown in Table 1.

The experimental results show that when the recovery rate of SF_6 gas was about 96.5%, the maximum positive deviation between the recovery rate measurement results of the detection module and that of the weighing method was 0.32%, and the maximum negative deviation was -0.24%, both of which are less than 0.5%, meeting the application requirements.

(a) Detection module recovery rate measurement (b) Weighing method measurement verification

Figure 4. SF_6 recovery rate validation experiment

Table 1. Recovery rate experimental data

Parameter name	1#	2#	3#	4#	5#	6#	7#	8#
Empty bottle quality (m_1/g)	8036	8036	8036	8036	8037	8037	8037	8037
SF_6 gas pressure before recovery (P_1/kPa)	398.1	594.5	789.3	989.2	398.1	594.5	789.3	989.2
Gas cylinder temperature before recovery (t_1/°C)	28.6	28.4	27.3	25.6	28.6	28.4	27.3	25.6
After filling the cylinder mass (m_2/g)	8236	8341	8462.5	8571	8236	8341	8462.5	8571
SF_6 gas pressure after recovery (P_2/kPa)	15.6	18.8	28.7	38.7	15.6	18.8	28.7	38.7
Gas cylinder temperature after recovery (t_2/°C)	28.1	28.5	27.4	25.8	28.1	28.5	27.4	25.8
Quality of cylinder after recovery (m_3/g)	8044	8046	8050	8055	8044	8046	8050	8055
Detection module recovery (η_1/%)	96.24	97.04	96.69	96.53	96.24	97.04	96.69	96.53
Calculated mass recovery (η_2/%)	96.00	96.72	96.72	96.45	96.48	97.04	96.94	96.63
Measurement deviation (Md/%)	0.24	0.32	-0.03	0.08	-0.24	0.00	-0.25	-0.10

4.2.Validation of the effective volume of SF6 electrical equipment

According to the theoretical model of effective volume measurement of the gas chamber of medium and high voltage electrical equipment, combined with the SF_6 gas metering module, the standard cylinders with 0.73 L, 4 L, 8 L, and 40 L volumes are selected as the standard container ends connected with the three-way valve. The bus bar and stop valve are arranged in the standard container module so that the size of different standard container volumes can be selected according to the volume of the container to be measured. The volume of the simulation vessel of the gas chamber of high-voltage electrical equipment was 40 L, 300 L, 600 L, and 1000 L respectively. SF_6 gas purity was not less than 99.99%

and the output pressure was not less than 0.5 MPa. The process of the verification system was shown in Figure 5. The effective volume verification experiment steps are as follows:

(1) Before the test, the standard vessel and experimental pipeline system were vacuumed with a vacuum pump to an absolute pressure below 10 Pa.

(2) We fill the 300 L, 600 L, and 1000 L containers (V_1) to be tested with about 0.5 MPa SF_6 gas, rest for 3 hours to fully balance it, and accurately record the initial pressure P_1.

(3) We open the valve between the standard sampling bottle and the container to be tested. After the gas pressure was balanced, we record the balance pressure P_2 of the container to be tested and the measured volume V_{1m} of the detection module.

(4) After the test was completed, we open the recharge module for SF_6 gas recharge. The whole measurement process was a closed loop, with no SF_6 gas emission and green environmental protection.

(5) According to the test results, the measurement deviation *Md* and the indication error of the detection module are calculated, as shown in Table 2.

The results show that when the container to be tested was 40 L, the maximum indication error was 2.06%. When the container to be tested was 300 L, the maximum indication error was -1.6%. When the container to be tested was 600 L, the maximum indication error was -2.52%. When the container to be tested was 1000 L, the maximum indication error was -1.51%. The above results can meet the demand for digital control in SF_6 gas recycling and reuse process of high voltage electrical equipment.

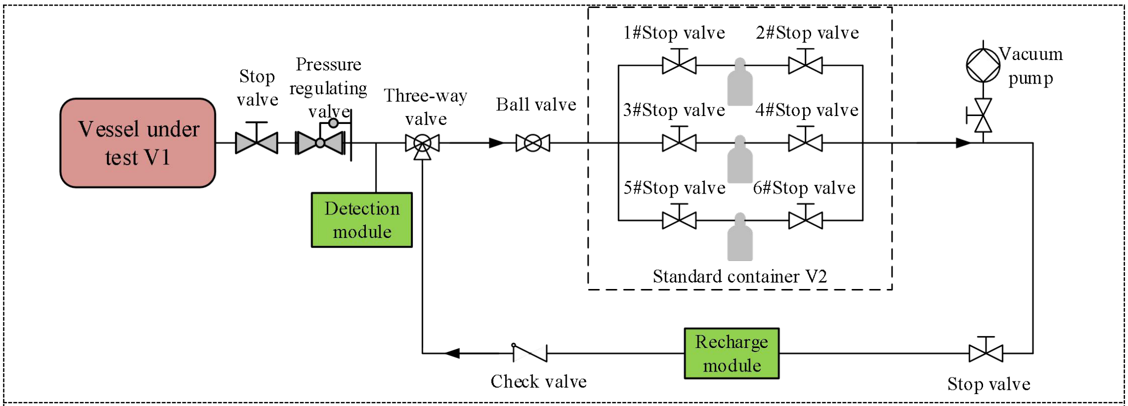

Figure 5. Verification and testing system for irregular chamber volume of high-voltage switch

Table 2. High voltage switch irregular chamber volume verification test data

Initial pressure P_1/MPa	Equilibrium pressure P_2/MPa	Vessel under test V_1/L	Standard sample bottle V_2/L	ΔP/MPa	The measured volume of detection module V_{1m}/L	Measurement deviation *Md*/L	Indication error/%
0.5155	0.5064	40	0.73	0.0091	40.6	0.6	1.56
0.5066	0.4977	40	0.73	0.0089	40.8	0.8	2.06
0.4979	0.4891	40	0.73	0.0088	40.6	0.6	1.43
0.4889	0.476	300	8	0.0129	295.2	-4.8	-1.60
0.4889	0.4762	300	8	0.0127	300.0	0.0	-0.01
0.4889	0.4762	300	8	0.0127	300.0	0.0	-0.01
0.4813	0.4807	600	0.73	0.0006	584.9	-15.1	-2.52
0.4813	0.4801	600	1.49	0.0012	596.1	-3.9	-0.65
0.4813	0.4795	600	2.22	0.0018	591.4	-8.6	-1.44
0.4849	0.4665	1000	40	0.0184	1014.1	14.1	1.41
0.4669	0.4492	1000	40	0.0177	1015.1	15.1	1.51
0.45	0.4328	1000	40	0.0172	1006.5	6.5	0.65

5. Conclusion

This paper analyzes the development and application status of SF_6 gas, the shortcomings of the whole life cycle management, and digital control technology. Based on the Beatty-Bridgman equation of state, the measurement principles of gas density, gas weight, and recovery rate of SF_6 gas in field inspection surface are studied. According to the changes in temperature and pressure before and after recovery, the mathematical models of gas density, gas weight, and recovery were established. The theoretical model of effective volume measurement of high-pressure switching chambers was established, which provides theoretical guidance for the selection of standard vessels under different chamber volumes and pressure. Finally, the SF6 gas recovery measurement and gas metering detection module were developed, and the performance of the detection module was verified. The main conclusions are as follows:

(1) When the SF_6 gas recovery rate was about 96.5%, the maximum positive deviation between the recovery rate measurement results of the gas metering module and that of the weighing method was 0.32%, and the maximum negative deviation was -0.24%, both of which are less than 0.5%.

(2) The effective volume verification results show that different standard containers combined with detection modules can be used to measure different volumes of the gas chamber to be measured. From the 40 L to 1000 L gas chamber to be measured, the indication error of the SF_6 gas measurement and detection module was less than 3%.

(3) The developed SF_6 gas measurement and detection module can simultaneously realize the effective measurement of SF_6 gas key parameters, which can provide important data support for SF_6 gas life cycle management and help realize the dual-carbon goal.

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