Sulfur Hexafluoride Gas Leakage Monitoring and Early-Warning Method for Electrical Power Facilities

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ABSTRACT Most transformer substations in power supply facilities rely on sulfur hexafluoride electrical equipment. A sulfur hexafluoride gas leak can cause serious health concerns if effective measures are not adopted in time. Therefore, in this study, a sulfur hexafluoride gas leakage monitoring, early-warning, and emergency disposal model was established. First, taking the main transformer chamber of an underground transformer substation as the research object, a 3D-model was built, and a numerical simulation was performed. Second, the simulation results were utilized to determine the dispersion and concentration distribution of the sulfur hexafluoride gas, identify concentration-sensitive areas, and arrange sensors based on the simulation results, to ensure early-warning in case of leaks. Then, a sulfur hexafluoride gas leakage monitoring and early-warning model was built based on the data collected using sensors at the monitoring points; thereafter, a construction method was developed for a sulfur hexafluoride gas leakage emergency disposal model, which can be referenced to establish a leakage gas recycling system. This paper also provides some recommendations regarding the determination of the optimal conditions for this emergency recycling device, which can be utilized to maintain the concentration of sulfur hexafluoride gas below a specified value and to construct a recycling time prediction model. The results of the study can provide a theoretical basis for sulfur hexafluoride gas leakage early-warning and emergency disposal, which will contribute to the prevention of suffocation-related accidents.

INDEX TERMS Sulfur hexafluoride, monitoring and early-warning, emergency recycling, numerical simulation.

I. INTRODUCTION

With a booming economy and rising power demand, it has become a common practice to build transformer substations in densely populated urban areas. Because of factors such as land shortage, substation construction often involves high-capacity equipment and underground development. Most substations utilize sulfur hexafluoride electrical equipment [1], with a 1000 ppm index used for sulfur hexafluoride gas leakage monitoring [2]. Based on expert knowledge and research results, it can be concluded that once a sulfur hexafluoride gas leak lowers the oxygen concentration to less than 19%, workers and maintenance staff will be exposed to potential asphyxiation. Sulfur hexafluoride gas is designated in the Kyoto Protocol of the United Nations as a greenhouse gas and has a significant impact on the greenhouse effect. Under a 100 year baseline, its impact on the greenhouse effect is 23,900 times that of carbon dioxide. Moreover, in the presence of arcs, partial discharges, and sparks, the decomposition products of sulfur hexafluoride gas, such as SF₂, SF₃, and SF₄, will react chemically with gas impurities, electrodes, and nearby solid insulating materials, forming several toxic and corrosive by-products. In a relatively sealed space, because the air is not circulating, these can cause significant harm to people. Thus, the consequences of a sulfur hexafluoride gas leak in a transformer substation are severe, and
methodological and technical solutions are needed to provide effective alerts to such leaks, along with corresponding emergency disposal methods.

Many research institutions and scholars have conducted studies on leakage pre-warning and emergency disposal systems, but few have given attention to the rules, prevention and control, and emergency disposal of leaking sulfur hexafluoride gas. Dong et al. [3] conducted an indoor hazardous gas diffusion test to simulate heavy gas leakage. Law et al. [4] used computational fluid dynamics (CFD) to evaluate the effect of topographical and wind conditions on the dispersion of chlorine leaks around the Gebeng industrial area of Malaysia. Baalisampang et al. [5] proposed a methodology for modeling a small liquefied natural gas (LNG) leak and its dispersion. Bubbico et al. [6] used CFD to analyze and compare the dispersions of two common toxic chemicals (chlorine and ammonia). Han et al. [7] performed a CFD simulation to study the effect of the leakage angle on the indoor SF$_6$ gas leakage and diffusion process. Starting from the numerical perspective, Li et al. [8] studied the dynamic leakage and dispersion of methane in a closed space and suggested using an oval model to predict the combustible area. In their study, an oval model was created by combining the aspect ratio and transverse length function. The developed engineering model (oval one) and numerical results were compared, and it was found that the engineering model could accurately predict the combustible area after reaching a stable state. Another study considered the recycling of sulfur hexafluoride gas in scrapped electrical equipment [9]. A review of the existing literature revealed that there have been few studies on the optimized locations for sensor monitoring points, prediction of the gas concentration distribution in the main transformer chamber, and emergency disposal of leaking sulfur hexafluoride gas. To prevent and control a sulfur hexafluoride gas leak in a transformer substation, at least the following three tasks should be given attention: (1) optimize the sensor locations to obtain the concentration dispersion of the sulfur hexafluoride gas in critically sensitive areas; (2) build a model for predicting the leakage and dispersion concentration in order to determine the most hazardous areas within the space, assisting personnel in staying away from these hazardous areas when evacuating after a sulfur hexafluoride leak, and facilitating emergency rescue work (with the model also potentially serving as the basis for procedure-writing and training); and (3) build an emergency recycling device to keep the sulfur hexafluoride gas concentration within the space below a specified value and allow the maintenance staff to quickly and safely enter the space to perform repair work.

In order to accomplish these tasks, the following work was performed in this study. ① Some basic information (such as the main influencing factors, boundary conditions, and selected models) required for the numerical simulation of the leakage and diffusion of sulfur hexafluoride gas was determined, and a numerical simulation was performed using the main influencing factors as variable parameters. ② A statistical analysis was performed to determine the most sensitive areas (the areas where the concentration of sulfur hexafluoride reaches 1000 ppm in the shortest time) and lay out the sensors on this basis to ensure that the sulfur hexafluoride gas concentration can be detected as soon as possible. ③ A method for the multi-area and multi-point continuous monitoring and collection of the sulfur hexafluoride gas concentrations was developed, and a sulfur hexafluoride gas leakage monitoring and early-warning model was built. ④ An emergency recycling device was developed to recycle the sulfur hexafluoride gas released into the air and maintain the sulfur hexafluoride gas concentration in the space within a specified range. The research results presented here will provide a theoretical basis for the monitoring, early-warning, and emergency disposal of sulfur hexafluoride leaks in the transformer substations used for supplying power.

II. OVERVIEW OF METHODS FOR CONSTRUCTING SULFUR HEXAFLUORIDE LEAKAGE MONITORING, EARLY-WARNING, AND EMERGENCY DISPOSAL MODELS IN SUBSTATIONS

A. MONITORING, EARLY-WARNING AND EMERGENCY RECYCLING PROCESSES FOR SULFUR HEXAFLUORIDE GAS IN TRANSFORMER SUBSTATIONS

A transformer substation monitoring, early-warning, and emergency recycling process operates as follows: when a sulfur hexafluoride gas leak occurs within a main transformer chamber, some sensors within the sulfur hexafluoride gas sensitive area will provide an alarm after the concentration reaches a specified value, and the emergency recycling device will be activated. Then, the device begins recycling the sulfur hexafluoride gas through an extraction vent in order to maintain the indoor sulfur hexafluoride gas concentration below 1000 ppm. At the same time, oxygen concentration sensors and alarms can also be installed to test the oxygen concentration, which can be referenced to set the startup and shutdown values of the emergency recycling device. Next, the maintenance staff can enter the main transformer chamber to begin maintenance. The emergency recycling device will automatically stop when the sulfur hexafluoride gas concentration is lower than a specified value, and it will start again when the sulfur hexafluoride gas concentration exceeds the specified value. The indoor equipment of the main transformer is shown in Figure 1.
B. OVERVIEW OF METHOD FOR BUILDING SULFUR HEXAFLUORIDE GAS LEAKAGE MONITORING AND EARLY-WARNING MODEL FOR TRANSFORMER SUBSTATION

In building a sulfur hexafluoride gas leakage monitoring and early-warning model, the sulfur hexafluoride gas leakage and dispersion in an underground transformer substation should be numerically simulated (because a CFD model can effectively describe the influence of complex terrain and obstacles on the gas flow and dispersion [10], [11]). Some monitoring points were arranged to analyze the dispersion of the sulfur hexafluoride gas, and some concentration-sensitive areas were identified. Some sensors were laid out according to the analysis results, and finally, a sulfur hexafluoride gas leakage monitoring and early-warning model was established using the data collected by the monitoring sensors and appropriate error correction. The framework is illustrated in Figure 2.

III. METHOD FOR BUILDING SULFUR HEXAFLUORIDE GAS LEAKAGE MONITORING AND EARLY-WARNING MODEL

A. NUMERICAL SIMULATION

1) RESEARCH OBJECT

The main transformer chamber within an underground transformer substation was taken as the research object. The chamber’s surrounding and top walls were all tightly sealed, and the chamber contained a transformer and heat exchanger with an extraction vent below it, and such accessories as a pipeline. The chamber measured 10 m in length, 8 m in width, and 7.5 m in height. Some leakage points were located at a valve on the pipe connecting the transformer to the heat exchanger as designed. According to the design, leaks could occur at three points. Point 1 has the coordinates of (5.4, 6, 2.5), point 2 has the coordinates of (3.1, 4, 1.95), and point 3 has coordinates of (2.6, 2.5, 4). The specific layout is illustrated in Figure 3. The gas leakage orifice for sulfur hexafluoride gas has been simplified to give it a circular shape with several diameters, including 0.5 mm, 1 mm, 2 mm, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 50 mm.

2) SETTING OF SIMULATION PARAMETERS

A hydromechanical transient simulation, in combination with an energy model, a standard turbulence model, and a component transport model, was performed. The initial conditions included a relative humidity of 45%, ambient temperature of 25 °C, and transformer operating pressure of 150,000 Pa (gauge). The boundary conditions included the following: (1) a mass-flow-inlet for the sulfur hexafluoride gas orifice; (2) pressure-outlet for the door and ground air extraction vent; and (3) walls for the equipment, pipeline, ground, and chamber.

B. DISPERSION SITUATION ANALYSIS

With a leak at point 1, which has a 5-mm orifice diameter, as an example, the dispersion process for the sulfur hexafluoride gas could be observed and analyzed. The release of the leaked sulfur hexafluoride gas was in the vertical downward direction and then horizontal.

1) GAS DISPERSION SITUATION 10 s AFTER LEAKAGE

The sulfur hexafluoride gas tended to be more concentrated around the floor below the gas leakage orifice, which was mainly because the chemical leaks quickly and because its density is higher than that of air. Thus, it gathered on the floor after leaking, and the mass fraction of the sulfur hexafluoride
gas in the mixed gas (composed of sulfur hexafluoride gas and air) at the floor below the gas leakage orifice very quickly exceeded 0.005, in other words, the concentration of sulfur hexafluoride gas exceeded 1000 ppm (see Figure 4 (1)).

2) GAS DISPERSION SITUATION 50 s AFTER LEAKAGE
As the sulfur hexafluoride gas continued to leak, the concentration within the main transformer continuously rose, and it was found that the concentration was above 1000 ppm in most of the areas at floor level and a few areas 1.5 m above from the floor (see Figure 4 (2)).

3) GAS DISPERSION SITUATION 100 s AFTER LEAKAGE
Many areas 1.5 m above the floor had a sulfur hexafluoride gas concentration greater than 1000 ppm (see Figure 4 (3)).

4) GAS DISPERSION SITUATION 200 s AFTER LEAKAGE
Most of the areas 1.5 m above the floor had a sulfur hexafluoride gas concentration greater than 1000 ppm. By this time, the main transformer chamber of the underground transformer substation had a sulfur hexafluoride gas concentration greater than 1000 ppm in most of its space (see Figure 4 (4)).

The changes of the mass fraction of sulfur hexafluoride gas in the mixed gas at monitoring points 0.1 m and 1.5 m above the floor are shown in Figure 5. Approximately 10 s after the leakage, the mass fraction of the sulfur hexafluoride gas in the mixed gas monitored at 0.1 m above the floor was greater than 0.005 (which meant the concentration exceeded 1000 ppm). This was consistent with the gas dispersion 10 s after the leakage. When the leakage continued for 200 s, the sulfur hexafluoride gas concentration monitored at 1.5 m above the floor was greater than 1000 ppm, which was in accordance with the gas dispersion 200 s after the leakage.

C. OPTIMAL SENSOR SETTINGS
1) EXPLANATION OF OPTIMAL SENSOR SETTING LOCATIONS
Based on a field survey, there were three places within the main transformer chamber where leakage could occur. Thus, the sensors had to initially be laid out at the best points for determining the specific location of a sulfur hexafluoride gas leak. In order to ensure the safety of personnel, a sulfur hexafluoride concentration of 1000 ppm and an oxygen content of 9% were set as alarm-producing values. The alarm thresholds for the sulfur hexafluoride gas infrared sensor (S1-GP-S) could be determined and configured based on the previously discussed information.

2) OPTIONAL LOCATIONS FOR SENSORS
The monitoring sensors had to be located within the main transformer chamber to track the changes in the sulfur hexafluoride gas concentration. The sensors could be located at monitoring points in two planes 0.1 m and 1.5 m above
the floor. The monitoring points in these two planes differed from each other only in height, and they were arranged in a pattern of five lines and five rows at intervals of 2 m and 2.5 m, respectively; this divided the planes into 16 rectangles. The monitoring points were placed at the tops of these rectangles. Because the farthest side of the planes was a wall, all the outmost monitoring points were pushed inward by 0.1 m. Because a few points of some rectangles were already occupied by equipment, it was not necessary to place sensors at those points. The monitoring points were located as shown in Figure 6, and their coordinate details are provided in Table 1.

The height settings of the monitoring points were based on the following two facts: (1) because it is a heavy gas, sulfur hexafluoride tends to gather on the floor, and most people stand and breath at approximately 1.5 m above the floor. Thus, monitoring points were located in two planes that were 0.1 m and 1.5 m above the floor. (2) The monitoring points located at the tops of the divided rectangles could be used to determine the areas in which the sulfur hexafluoride gas concentration first exceeded 1000 ppm.

3) DETERMINING SENSOR LOCATIONS
Based on the method for determining the sensor points reported in a previously published article [2], the simulation results were used to determine that when a leak occurred at point 1, the sulfur hexafluoride gas concentration first exceeded 1000 ppm at monitoring points 8 and 27 seven times, which was more often than the times that it first exceeded this limit at the other points. When a leak occurred at point 2, the sulfur hexafluoride gas concentration first exceeded 1000 ppm at monitoring points 24 and 32 eight times, which was more often than the times that it first exceeded this limit at the other points. When a leak occurred at point 3, the sulfur hexafluoride gas concentration first exceeded 1000 ppm at monitoring points 2 and 1 seven times, which was more often than the times that it first exceeded this limit at the other points. Therefore, it was determined the sensors should be located at monitoring points 8, 27, 24, 32, 2, and 1, as shown in Figure 6.

D. GAS LEAKAGE MONITORING AND EARLY-WARNING MODEL
1) BUILDING THE MODEL
Based on the method used for the model in a previously published article [2], a gas leakage monitoring and early-warning model could be established through regressing and fitting the simulated data [12]–[17], in which the gas leakage orifice diameter was x, leakage time was y, and sulfur hexafluoride gas concentration was z. Table 2 shows the model of monitoring point 24 for a leak occurring at point 1 [2]. The concentration values could be acquired by substituting different values for the gas leakage orifice diameter and leakage time into the model.

For example, in Table 2, with x = 5, 10 and 15, and (x, y) \( \notin \) C, the model formula shown in 1 can be used to determine the concentration:

\[
    z = d_{00} + d_{10} \times x + d_{01} \times y + d_{20} \times x^2 + d_{11} \times x \times y + d_{02} \times y^2 + d_{21} \times x^2 \times y + d_{12} \times x \times y^2 + d_{03} \times y^3 \quad (1)
\]

where

\[
    d_{00} = -0.0007524; \quad d_{10} = +0.000416;
\]
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**TABLE 1.** Coordinates of monitoring points.

| Monitoring points | Coordinates | Monitoring points | Coordinates | Monitoring points | Coordinates | Monitoring points | Coordinates |
|-------------------|-------------|-------------------|-------------|-------------------|-------------|-------------------|-------------|
| 1                 | 0.1, 0.1, 1.5 | 11                | 0.1, 7.5, 1.5 | 21                | 0.1, 5, 0.1 | 31                | 2, 0.1, 0.1 |
| 2                 | 0.1, 5, 1.5   | 12                | 2, 0.1, 1.5   | 22                | 0.1, 9.9, 0.1 | 32                | 2, 5, 0.1   |
| 3                 | 0.1, 9.9, 1.5 | 13                | 2, 5, 1.5    | 23                | 4.0, 1, 0.1  | 33                | 2, 9.9, 0.1 |
| 4                 | 4.0, 1, 1.5   | 14                | 2.9, 9, 1.5  | 24                | 4, 5, 0.1   | 34                | 6.0, 1.0    |
| 5                 | 4.5, 1.5      | 15                | 6.0, 1.5     | 25                | 4, 9.9, 0.1 | 35                | 6.5, 0.1    |
| 6                 | 4.9, 9.1, 1.5 | 16                | 6, 5, 1.5    | 26                | 7.9, 0.1, 0.1 | 36            | 6.9, 9, 0.1 |
| 7                 | 7.9, 0.1, 1.5 | 17                | 6, 9.9, 1.5  | 27                | 7.9, 5, 0.1 | 37                | 7.9, 2.5, 0.1|
| 8                 | 7.9, 5, 1.5   | 18                | 7.9, 2.5, 1.5| 28                | 7.9, 9.9, 0.1 | 38            | 7.9, 7, 5, 0.1|
| 9                 | 7.9, 9.9, 1.5 | 19                | 7.9, 7.5, 1.5| 29                | 0.1, 2.5, 0.1 |               |             |
| 10                | 0.1, 2.5, 1.5 | 20                | 0.1, 0.1, 0.1| 30                | 0.1, 0.1, 0.1|               |             |

**TABLE 2.** Regression models.

| Gas leakage orifice diameter (mm) | Time- and gas leakage orifice diameter-induced change in leaking gas concentration |
|-----------------------------------|---------------------------------------------------------------------------------|
| y<69, z<10^{-4}                  |                                                                                  |
| x=0.5,                            |                                                                                  |
| z=a0+a1*cos(a*x)+a2*sin(a*x)+a3*cos(2*a*x)+a4*sin(2*a*x)+a5*cos(3*a*x)+a6*sin(3*a*x)+a7*cos(4*a*x)+a8*sin(4*a*x)+a9*cos(5*a*x)+a10*sin(5*a*x)+a11*cos(6*a*x)+a12*sin(6*a*x)+a13*cos(7*a*x)+a14*sin(7*a*x)+a15*cos(8*a*x)+a16*sin(8*a*x) |
| y<82, z<10^{-4}                  |                                                                                  |
| x=1                               |                                                                                  |
| z=b0+b1*cos(b*x)+b2*sin(b*x)+b3*cos(2*b*x)+b4*sin(2*b*x)+b5*cos(3*b*x)+b6*sin(3*b*x)+b7*cos(4*b*x)+b8*sin(4*b*x)+b9*cos(5*b*x)+b10*sin(5*b*x)+b11*cos(6*b*x)+b12*sin(6*b*x)+b13*cos(7*b*x)+b14*sin(7*b*x)+b15*cos(8*b*x)+b16*sin(8*b*x) |
| y<5, z<10^{-4}                   |                                                                                  |
| x=2                               |                                                                                  |
| z=c0+c1*cos(c*x)+c2*sin(c*x)+c3*cos(2*c*x)+c4*sin(2*c*x)+c5*cos(3*c*x)+c6*sin(3*c*x)+c7*cos(4*c*x)+c8*sin(4*c*x)+c9*cos(5*c*x)+c10*sin(5*c*x)+c11*cos(6*c*x)+c12*sin(6*c*x)+c13*cos(7*c*x)+c14*sin(7*c*x)+c15*cos(8*c*x)+c16*sin(8*c*x) |
| (x, y) ∈ C, z=x0+x1*y+d01*x+y+d02*x^2+d03*y^2 |                                                                                  |
| (x, y) ∈ D, z=x0+x1*y+d21*x+y+d22*x^2+y+d23*x^3 |                                                                                  |

Because all the correlation coefficients of the models listed in Table 2 are greater than 0.9, it can be inferred that the respective regression fitting models are fairly accurate. They can provide a theoretical basis for predicting the leakage and dispersing concentration of sulfur hexafluoride in the main transformer chamber of an underground transformer substation.

2) MODEL ERROR CORRECTION

a: METHOD FOR CORRECTING MODEL ERROR

The mass fractions of sulfur hexafluoride monitored at 25 s, 45 s, 65 s, 85 s, 105 s, 125 s, 145 s, 165 s, 185 s, 205 s, 225 s, and 245 s by all the sensors and computed using the models against different gas leakage orifice diameters were compared to determine the errors. Because some errors were quite significant, the corresponding models were corrected accordingly.

If the correction coefficient is m, the corrected model will be 

\[ z' = m \times z \]

The correction coefficient of a model was equal to the simulated data divided by the computed data. After the sorting, classification, and regression fitting of the data, it was possible to generate a fitting formula for the leakage time (s) and correction coefficient. In this formula, the leakage time was set as y, while the correction coefficient was m.

b: CASES OF MODEL ERROR CORRECTION

The model resulting from the regression fitting of the data collected from monitoring point 24 with a leak at point 1 was
taken as an example; some errors appear to be significant when \( x = 2 \) mm, 5 mm, 10 mm, 15 mm, and 20 mm. The corresponding formula for the correction coefficient is provided in Table 3, and the post-correction formula errors are listed in Table 4.

According to Table 4, the largest error after correction is 9.2857% (below 10%), indicating that the corrected model is relatively accurate. Therefore, the models corresponding to other monitoring points can be corrected similarly in order to generate leakage- and dispersing-concentration-prediction models with higher accuracy.

With the case where \( x = 10 \) in Table 3 as an example, the correction coefficient for formula 2 is shown below:

\[
m = (h1 \times y^5 + h2 \times y^4 + h3 \times y^3 + h4 \times y^2 + h5 \times y + h6) 
= (y^5 + h7 \times y^4 + h8 \times y^3 
+ h9 \times y^2 + h10 \times y + h11)
\]

\[m = 1\]

where

\[
h1 = +0.977362296107704; \quad h2 = -21.556111659111;
\]

\[
h3 = +148.488818620726; \quad h4 = -291.175251924329;
\]

\[
h5 = -75.4443265532684; \quad h6 = -16.839773042804;
\]

\[
h7 = -23.9981328342724; \quad h8 = +134.52933888989;
\]

\[
h9 = +225.944058541348; \quad h10 = +44.9417735946604;
\]

\[
h11 = +9.05359482353389.
\]

### IV. SULFUR HEXAFLUORIDE GAS LEAKAGE EMERGENCY DISPOSAL MODEL

The sulfur hexafluoride gas leakage emergency disposal model consisted of an emergency recycling device and a recycling time prediction model. The emergency recycling device could recycle the sulfur hexafluoride gas leaked into the air, and the recycling time prediction model could predict the time required to recycle the sulfur hexafluoride gas.

### A. EMERGENCY RECYCLING DEVICE

1) STRUCTURE OF EMERGENCY RECYCLING DEVICE

The overall structure of the emergency recycling device is illustrated in Figure 7 and Figure 8, which show that the...
device consisted of a mechanical drive mechanism, support frame, active shutter, collection vessel, programmable logic controller (PLC), electric butterfly valve, and pipeline.

2) WORKING PRINCIPLE OF EMERGENCY RECYCLING DEVICE

After a sensor sends an alarm, the PLC in the emergency recycling device transmits a signal to activate the electric butterfly valve. When the valve reaches the appropriate location, a feedback signal is sent to the PLC, and the mechanical drive mechanism starts. End A of the active shutter ascends to a designated height, and its limit switch is triggered to turn off the mechanical drive mechanism. At this time, the bottom of the collection vessel is closed to stop the sulfur hexafluoride from escaping and entering the bottom space, and the sulfur hexafluoride recycling begins.

After the emergency recycling device starts working, if an alarm cancelling message is received, the PLC will turn off the electric butterfly valve, which returns to the appropriate position and sends a feedback signal back to PLC to start the mechanical drive mechanism again. Then, end B of the active shutter descends to the designated place and triggers its limit switch to turn off the mechanical drive mechanism. Finally, the sulfur hexafluoride recycling is stopped, and the bottom of the collection vessel is opened again. The process flow is depicted in Figure 9.

B. RECYCLING TIME PREDICTION MODEL

Using the recycling prediction model, the recycling time can be obtained based on the leakage orifice diameter and leakage location.

The construction method for the recycling time prediction model was as follows: Under the determined extraction pressure, the recycling of the sulfur hexafluoride gas in the main transformer chamber of the substation is simulated for different leakage locations and leakage orifice diameters. Then, the simulation results are used to determine the time required for the sulfur hexafluoride concentration to stably remain below 1000 ppm and the oxygen content to stably remain above 19% (which is the recycling time). Then, by grouping according to the leakage location, the regression fitting for the leakage orifice diameter and its corresponding recycling time are used to obtain three sets of fitting formulas, which constitute the recycling time prediction model.

V. SETTING OF EMERGENCY RECYCLING DEVICE CONDITION

A. NUMERICAL SIMULATION

The research object for recycling was the main transformer chamber, where the gas leakage orifice diameter was 50 mm. The required model and grid were similar to those used in the previous leakage numerical simulation, and the simulation parameters were almost the same. Only minor modifications were made to the boundary conditions, and a negative pressure was provided for the air extraction vent. In the simulation, the air extraction pressure in the emergency recycling device was changed to simulate the recycling of sulfur hexafluoride against different air extraction pressures.

B. RECYCLING ANALYSIS

As an example, the dispersion of the gaseous sulfur hexafluoride is demonstrated in Figure 10 for recycling after a leak occurs at point 1; the air extraction pressure for the device was $-1 \text{ kPa}$. 

FIGURE 7. Outline view.

FIGURE 8. Localized view.

FIGURE 9. Recycling process.
1) GAS RECYCLING UPON SENSOR ALARM
In this case, the sensor detects excessively dense sulfur hexafluoride and generates an alarm, but the emergency recycling device is not activated yet, and the gaseous sulfur hexafluoride continues leaking. The indoor sulfur hexafluoride concentration rises sharply, and exceeds 1000 ppm in a few areas, as shown in Figure 10 (1).

2) GAS RECYCLING IMMEDIATELY AFTER DEVICE IS ACTIVATED
In this case, the emergency recycling device has just started, but because it takes a period of time to set up the device (the required time is 30 s), the sulfur hexafluoride recycling has not yet begun, and the indoor sulfur hexafluoride concentration continues to rise. The sulfur fluoride concentration exceeds 1000 ppm, as shown in Figure 10 (2).

3) GAS RECYCLING AFTER DEVICE HAS BEEN WORKING FOR 1460 s
The emergency recovery device has been activated for 1460 s. Because of the effect of pumping, the sulfur hexafluoride concentration in most indoor areas has dropped below 1000 ppm, as shown in Figure 10 (3).

4) GAS RECYCLING AFTER DEVICE HAS BEEN WORKING FOR 1500 s
In this case, the indoor sulfur hexafluoride concentration has dropped below 1000 ppm, and the indoor air is essentially harmless to the human body, as shown in Figure 10 (4).

C. DETERMINING CONDITIONS FOR EMERGENCY RECYCLING DEVICE
After several groups of experiments, a curve was drawn that shows the correlation between recycling air extraction pressure $P$ (Pa) and time $t$ (s) required to obtain a sulfur hexafluoride concentration below 1000 ppm, as shown in Figure 11. It could be used to find regression model 3 for the correlation between the air extraction pressure and time required for stabilization as follows:

$$P = p_1 + p_2 \times t + p_3 \times t \times 0.5 \times \ln(t) + p_4 \times t / \ln(t) + p_5 \times \ln(t)$$

(3)

where

$$p_1 = +4264.81259816733; \quad p_2 = -10.0497250693862;$$

$$p_3 = -47.5735069701139; \quad p_4 = +131.453194460182;$$

$$p_5 = -195.63607669359.$$

After regression and fitting, fitting coefficient $R$ of the formula was determined to be 0.99774, which suggested a satisfactory fitting effect and minor errors. A comparison of the fitting values from models using the original data revealed that they agreed very well with each other. Thus, it could be assumed that the fitting formula produces reliable results within a specific range, as shown in Figure 12. It is possible to use this regression model to accurately determine the time required to obtain a sulfur hexafluoride concentration of less than 1000 ppm for different air extraction pressures. The
model can provide a theoretical basis for determining the conditions of an emergency recycling device.

In accordance with Figure 11 and the regression model, although the sulfur hexafluoride concentration could quickly be stabilized below 1000 ppm under other air extraction pressures, a comprehensive examination of the emergency recycling device’s air extraction pressure and time required to reach stability suggested that the device cost should be reduced as much as possible on the premise of ensuring a relatively short period of time. The air extraction pressure condition for the emergency recycling device was finally set to $-1 \text{kPa}$.

### VI. BUILDING RECYCLING TIME PREDICTION MODEL

Using the leakage orifice diameter as a variable parameter, the recycling of sulfur hexafluoride in the main transformer chamber was simulated at the three leakage locations. Based on the simulation results, the fitting formula for the leakage orifice diameter (mm) and time (s) required to reach a stable sulfur hexafluoride concentration of less than 1000 ppm and an oxygen content greater than 19% was obtained by regression fitting, as listed in Table 5. In the fitting formula, the leakage orifice diameter is $x$, and the time required to reach a stable sulfur hexafluoride concentration of less than 1000 ppm and an oxygen content of greater than 19% (recycling time) is $y$.

| Leakage location | Relationship between recycling time and leakage orifice diameter |
|------------------|------------------------------------------------------------------|
| Point 1          | $y = l_1 x^2 + l_2 x + l_3$                                      |
| Point 2          | $y = m_1 x^2 + m_2 x + m_3$                                      |
| Point 3          | $y = n_1 x^2 + n_2 x + n_3$                                      |

The fitting formula when the leakage location is point 1 in Table 5 can be taken as an example. At this time, the fitting formula is 4, as shown below:

$$ y = 11 \times x^2 + 12 \times x + 13 \quad (4) $$

where

$$ l_1 = -0.853803001396724; $$

$$ l_2 = +72.286669426952869; $$

$$ l_3 = -1.752587158719537. $$

As listed in Table 5, three sets of fitting formulas were obtained through regression fitting. The $R$ coefficients of these formulas obtained through regression fitting are all greater than 0.9. Thus, it could be determined that these empirical formulas are relatively accurate. These fitting formulas obtained through regression fitting constitute the recycling time prediction model. This model can be used to predict the recycling time required under different leakage conditions. The model can be used online and has a rapid solution speed, which can provide useful assistance in arranging for emergency disposal after recycling.

### VII. CONCLUSIONS

This study considers methods for building sulfur hexafluoride leakage monitoring, early-warning, and emergency disposal models for an underground transformer substation. Sulfur hexafluoride leaks were first simulated. Then, the dispersion pattern in the main transformer chamber of the underground transformer substation was analyzed. The concentration-sensitive areas were determined based on the simulation results, and the sensors were configured on this basis. A model for predicting the sulfur hexafluoride leakage and dispersing concentration within the main transformer chamber was built. Next, an emergency disposal model was proposed, and the overall structure and working principle of its emergency recycling device were determined. Then, the construction method for its recycling time prediction model was proposed. Finally, the recycling process was simulated and analyzed to determine the optimal conditions for the emergency recycling device, and a recycling time prediction model was constructed using regression fitting. This was not only helpful in assessing the consequences of sulfur hexafluoride leakage events in similar transformer substations but could also effectively avoid and alleviate the harm to the environment and personnel. The results of this study are of great significance for the emergency disposal of harmful gas after an unexpected threat to public safety.
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