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Fire Hazard Detection for Power Cable Tunnel

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The early fire monitoring of cable tunnels is very important to ensure their safe operation and maintenance. Partial discharge and cable overheating are the main causes of power cable tunnel fires. To discover fire hazards in time, experiments were designed for the partial discharge of epoxy resin and cables and for cable overheating. The experimental results showed that they will emit many particles with specific diameters and release volatile organic compounds (VOCs) during cable discharge and cable overheating; therefore, we propose that the count of emission particles with specific diameters and the concentration of VOCs can be used as criteria for discovering fire hazards in power cable tunnels. Finally, the implementation of the fire hazard alarm method is presented by monitoring the concentration trends of VOCs and particles. The research results can provide guidance for the design of power cable tunnel fire warning systems and related fire warning standards.

1. Introduction

1.1 Cable fire identification

With the development of urbanization, power transmission cables have gradually replaced overhead transmission lines because of their advantages of not occupying ground space, not affecting the appearance of the city, being less affected by natural conditions such as severe weather, and being able to expand to higher voltage levels and larger transmission capacities. In recent years, the undergrounding of urban power transmission overhead lines in large cities in China has been completed. Medium- and high-voltage power cables, as the main branches in distributed networks, should have high security and reliability. (1–3)

There are many fire hazards in power cable tunnels. The sheath layer, cross-linked polyethylene (XLPE) cable, and epoxy resin in the cable joints of power cables are combustible materials, coupled with the fact that the cable channel exhibits spatial closure characteristics. The hidden fire points are difficult to find at the initial stage; therefore, it is very difficult to extinguish a fire early, so the identification of potential fire hazards in time is of great significance. Current studies on fire safety in power cable tunnels mainly focus on two aspects: tunnel fire monitoring and tunnel fire environment simulation.

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Temperature sensors are widely used for fire safety in power cable tunnels, and they generally exhibit good performance in monitoring cable fires in terms of accuracy, precision, and calibration.(4,5) Some sensors, such as smoke and CO/CO_2 sensors, have also been used to detect gases volatilized during combustion.(6) Recently, image-based fire recognition techniques have been applied with the advancement of deep learning.(7,8) A temperature detector, a smoke detector, and a temperature detector were used to test the fire alarm sequence, and the effect of fire detector sensitivity was explored.(9) Moreover, it has been reported that some cable fire monitoring techniques based on multicriteria fusion can achieve better fire alarm results.(10)

In recent years, many studies have been conducted to simulate a power cable tunnel fire environment. Liu *et al.*(11) investigated fire temperature distribution and ceiling temperature prediction in a closed utility tunnel. Xu *et al.*(12) studied the combustion characteristics of a single 110 kV cable fire accident and experimentally compared the cable combustion behaviors under different layouts. An *et al.*(13) analyzed the effect of cable interlayer spacing on the fire propagation characteristics of interlayer cables through a series of experiments on cable combustion in tunnels. Dong *et al.*(14) constructed a small-scale fire simulation model and obtained the relationship between flue gas temperature and fire source distance. Fisher *et al.*(15) found in a series of tests that the time to failure was highly reproducible and strongly dependent on cable temperature. Sun and Xu(16) proposed a novel automatic data generation method to perceive the ceiling temperature distribution in tunnel fires based on a neural network using limited real-time sensor data.

In summary, previous studies on fire alarm systems in power cable tunnels have mostly focused on traditional fire detection methods based on smoke, temperature, or flame detection and on cable combustion characteristics, which cannot simultaneously meet the requirements of early fire detection.

In this study, we designed a surface discharge experiment for an epoxy resin and XLPE cable, which is generally used in power cable tunnels, and an overheating experiment for an XLPE cable, to study the characteristic criteria of partial discharge and cable overheating. We found that the overheating cable would emit a large number of nanometer-sized particles (called nanoparticles) and release VOCs during discharge and cable overheating; hence, we propose a new method of discovering the potential fire hazards in power cable tunnels in the very early fire stage by detecting the count of nanoparticles and the concentration of VOCs released.

1.2 Fire hazard detection

The development of tunnel cable fires is a gradual process.(17) It can be divided into normal, overheating, smoking, and combustion stages, as shown in Fig. 1.

To better prevent the occurrence of tunnel fires, in this paper, we propose a method of discovering tunnel fire hazards by detecting emitted particles with specific diameters as well as the characteristic gases in the early development stage of tunnel cable fires, so we can send a timely alarm during cable overheating or the very early development stage of a tunnel fire.

The single partial discharge of power cables is relatively weak, but if it lasts for a long time, it will cause surrounding insulation failure, insulation breakdown, and short circuit, which is one

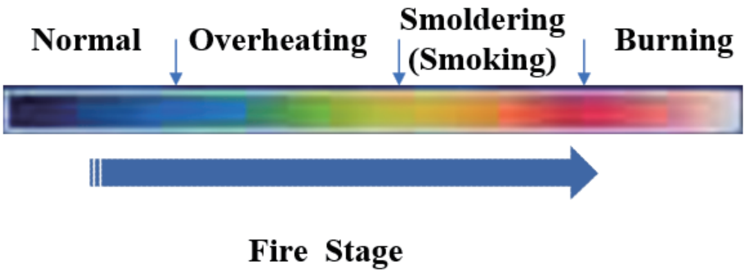


Fig. 1. (Color online) Fire development stages in cable tunnel.

of the main sources of power cable tunnel fires.(17) However, when the cable is overheated for a long time, its insulation layer accelerates aging, which causes insulation failure and fire.(18) Therefore, partial discharge and cable overheating are the main hidden dangers of power tunnel fires.

Some interesting and challenging studies have emerged in recent years on the detection of characteristic gases in early cable fires. PVC cable insulation is obtained by adding various additives such as plasticizers, stabilizers, inorganic fillers, and antioxidants to the polymer PVC matrix. When the cable insulation is heated, it volatilizes a variety of gases with different compositions as temperature increases.(19) By monitoring these characteristic gases, fires can be detected during the early stages of their development. Li(20) demonstrated by experiments that a PVC insulation jacket releases gaseous substances, mainly plasticizers such as dioctyl phthalate (DOP), at 150 °C. Chen and Yi(21) found that it would release mixed gas vapors with the majority of plasticizers such as DOP in the early stage of electrical fire development, which is in the low temperature range of 150–220 °C. The PVC cable insulation layer in the temperature range of 200–340 °C begins to degrade significantly and releases HCl, H_2O, CO_2, plasticizers, and so forth.(22–24) At 240 °C or higher temperatures, PVC cable burning may occur. (25) The characteristic gases used for early fire warnings represent a more advanced technology. However, owing to the different additives in different types of cable, the characteristic gases volatilized during the overheating stage or early cable fires vary significantly. Because the compositions of different cables differ, the characteristic gas of thermal volatilization must be tested and measured for specific cables.

Pyrolytic particles were used to identify fire hazards in our study. When a cable is overheated and reaches its heat limit, it emits many tiny particles, which are so small that the human eye cannot recognize them. At the same time, when an electric arc or spark occurs on the surface of the insulation material or cable, it leads to the emission of a large number of particles. These particles scatter in the air, resulting in a rapid increase in their concentration because of the closure of the power cable tunnels, which is tens of times beyond the normal level. Therefore, different fire risk levels can be reflected by different particle concentrations. Particle counting can effectively identify cable discharge and overheating status, determine fire hazards, and identify cable fires early.

We built a simulation environment for epoxy resin discharge and cable overheating, investigated the variation in particle count in the air when the cable was discharged, and studied the time series distribution of particle concentration and characteristic gas concentration when the cable was overheated. Experiments have proven that VOCs can be used as an early characteristic gas for fire detection, and we can effectively detect fire hazards by monitoring the particle count and VOC concentration in a power cable tunnel.

2. Experiments

2.1 Discharge test

The design of the discharge system is shown in Fig. 2. It uses a power frequency AC power supply, and the high-voltage power output terminal is connected to a water resistor, which plays a protective and voltage-dividing role in the entire device system. The other end of the water resistor is connected to the needle electrode of the discharge device to form a high-voltage electrode. The plate electrode in the device was grounded and a sampling resistor was connected in series to the grounding wire. One end of the high-voltage probe was connected to the needle electrode to collect voltage data at the needle electrode, and the other end was connected to an oscilloscope. The sampling resistor in the grounding wire converted the discharge current pulse into a voltage waveform and displayed it on an oscilloscope. A digital camera was used to collect discharge images.

Four sets of surface discharge experiments were conducted on two materials at different excitation voltages for a duration of 20 s. The surface discharge devices are shown in Figs. 3(a) and 3(b). In each figure, two wires are connected to a high-voltage power output terminal on one side and electrodes on the other side. The sample of insulating material is placed between the electrodes.

The insulating material samples were an epoxy resin and XLPE cable (epoxy resin: 45 mm diameter and 1 mm thickness; XLPE cable: 45 mm diameter and 3 mm thickness).

2.2 Overheating test

A heating rod was used to directly heat the wire core at the end of the high-voltage cable to simulate the situation when the temperature of the power cable joint and metal wire core

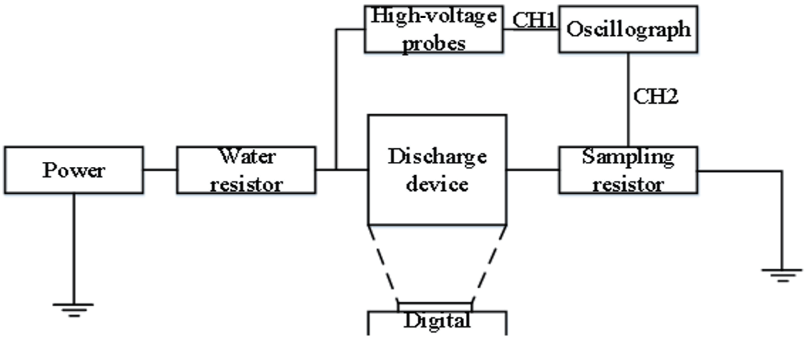


Fig. 2. Discharge system.

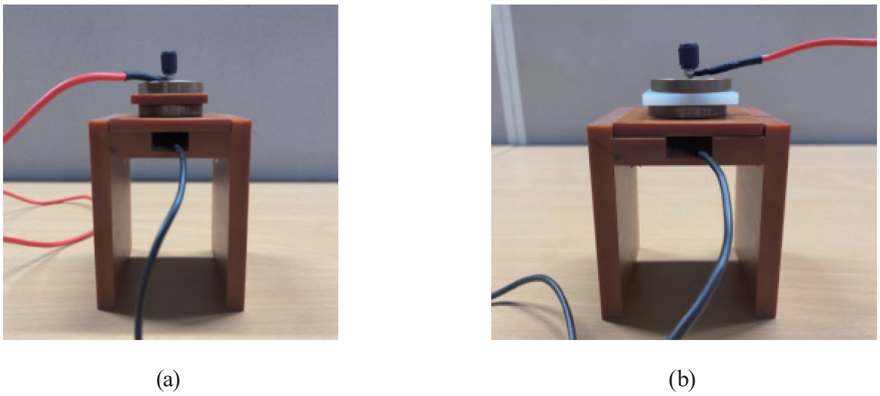

(a) (b)

Fig. 3. (Color online) (a) Epoxy resin and (b) cable discharge devices.

increased abnormally in an actual situation. The devices and materials used in this experiment are shown in Fig. 4.

The experimental method was as follows: a ring of the same size as the copper core was cut in the middle of the asbestos board and sleeved into the copper core, with one side close to the cutting surface of the power cable. The heating rod was evenly covered on the exposed copper core at one end of the power cable and fixed with a throat clamp. The temperature control circuit was composed of a temperature control meter, relay, heating rod, and monitoring device. The tip of the thermocouple in the control circuit touched the surface of the heating rod to measure the heating temperature of the heating rod. The opening and closing of the relay maintained the heating temperature of the heating rod near the set temperature to achieve the local heating of the cable. The heating temperature of this experiment was 150 ℃ and the heating duration was 10 min.

2.3 Sensing instruments

In the experiment, we use different gas sensors to detect the concentrations of gases. For VOCs, the gas sensor model is GTYQ-DX101, which is a catalytic combustion sensor. For both CO and H_2, the sensor model is GQ-DX101, which is an electrochemical gas sensor. The particle counter model is CLJ-3016, which is a laser particle counter.

3. Results and Discussion

3.1 Discharge test result

3.1.1 Particle emission analysis

During the experiment, a dust particle counter was used to count the number of particles with diameters below 0.3, 0.3–0.5, 0.5–1, and 1–2.5 μm in the air. The discharge experiments were

(a) (b) (c)

Fig. 4. (Color online) Cable overheat test device. (a) Heating rod, (b) temperature control meter, and (c) relay.

conducted on the epoxy resin and XLPE cable, and the cumulative particle count (the sum of the numbers of particles with four different diameters) curves under different voltage levels are shown in Fig. 5. Figures 5(a) and 5(b) show the particle count curves for the surface discharge experiment of the epoxy resin and XLPE cable, respectively.

The counts of particles of various sizes during the surface discharge experiment for each group were statistically analyzed, and the statistical results are shown in Table 1. The experimental data show that with the discharge intensity, the number of nanoparticles produced during cable overheating increases, and at the same time, the change range of the number of nanoparticles is larger in the epoxy resin than in the XLPE cable. With the discharge voltage, the increase in the slope of the nanoparticle number curve accelerates, which means that the scene of nanoparticles generated by discharge is clearer. The discharge experiments of both the XLPE cable and the epoxy resin demonstrated this.

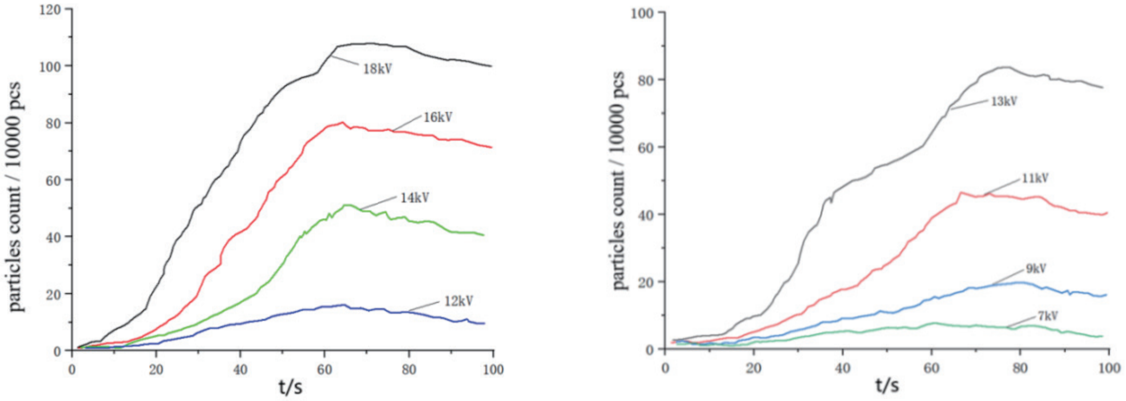
3.1.2 Volatilized gas analysis

The concentrations of CO, H_2, and VOCs were monitored during the experiment. With the discharge intensity, the concentration of hydrocarbon gas released by the cable and the corresponding VOC concentration increased significantly. The CO concentration changed during the experiment, whereas the H_2 concentration remained unchanged. Table 2 shows the gas concentration peak values for the different discharge intensities. The VOC concentration increases almost linearly with the discharge voltage during the surface discharge of the epoxy resin and cable, and the concentration of the VOC characteristic gas of the epoxy resin is higher than that of the cable.

3.2 Overheating test result

3.2.1 Particle emission analysis

During the experiment, particles with diameters below 0.3, 0.3–0.5, 0.5–1, and 1–2.5 μm in the air were counted using a dust particle counter. We conducted six overheating experiments on



(a) (b)

Fig. 5. (Color online) Curves of particle counts during surface discharge. (a) Epoxy resin and (b) XLPE cable.

Table 1
Statistics of particle data in surface discharge.

Count of particles (10000 pcs)		Epoxy resin	Cable
<0.3 μm	Average value (under normal condition)	0.7542	0.8331
	Peak value (discharge)	100.53	90.821
0.3–0.5 μm	Average value (under normal condition)	0.0325	0.0354
	Peak value (discharge)	0.1088	0.0838
0.5–1 μm	Average value (under normal condition)	0.0108	0.0241
	Peak value (discharge)	0.0718	0.0519
1–2.5 μm	Average value (under normal condition)	0.0008	0.0014
	Peak (discharge)	0.0138	0.0082

Table 2
Statistics of gas concentrations in surface discharge.

Gas concentration/ppm		Epoxy resin	Cable
CO	Average value (under normal condition)	0.3	0.3
	Peak value (discharge)	2.1	1.3
H_2	Average value (under normal condition)	0.1	0.1
	Peak value (discharge)	0.2	0.3
VOCs	Average value (under normal condition)	0	0
	Peak value (discharge)	153.5	97.2

the cable and selected one of the six groups of sample data to draw the change curve of the particle count with each particle size, as shown in Fig. 6.

We conducted statistics and analysis on the peak value data of particles of different sizes during the cable overheating test for each group. The statistical results are shown in Table 3. The experimental results showed that the overheating cable decomposed and released nanoparticles,

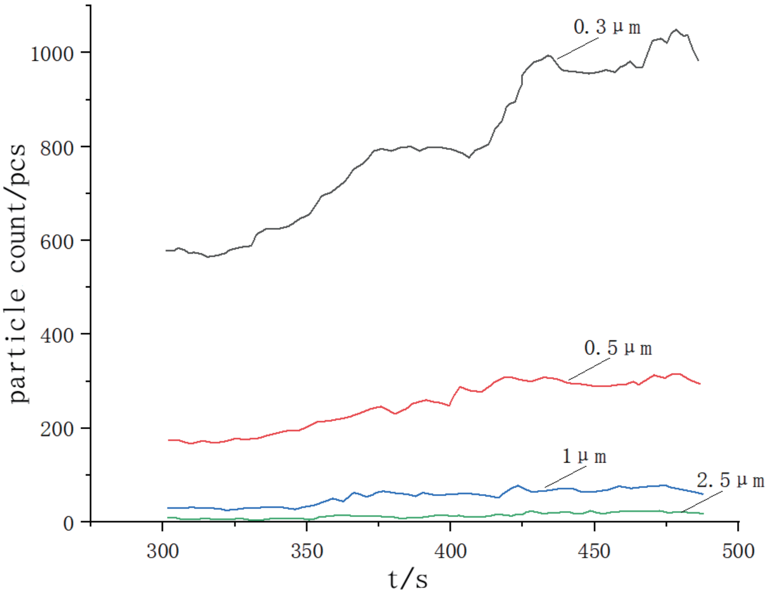


Fig. 6. (Color online) Curves of particle count with different diameters.

Table 3
Discharge particle count statistics during cable overheating.

Particle/piece		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
<0.3 μm	Average value (under normal condition)	5846	5318	4677	5102	4933	4751
	Peak value (overheating)	15346	15239	16028	15694	14762	16311
0.3–0.5 μm	Average value (under normal condition)	187	190	175	215	249	188
	Peak value (overheating)	382	419	397	451	477	365
0.5–1 μm	Average value (under normal condition)	53	46	57	43	50	41
	Peak value (overheating)	78	81	92	76	85	84
1–2.5 μm	Average value (under normal condition)	16	9	22	10	17	21
	Peak value (overheating)	41	30	52	28	47	66

and the count of particles with diameters below 0.3 um increased most significantly. Moreover, the larger the particle diameter, the smaller the count change caused by cable overheating.

3.2.2 Volatilized gas analysis

Concentrations of CO, H_2, and VOCs were monitored during the experiment. We conducted six overheating experiments on the cable and selected one of six groups of sample data to draw the concentration curve of each characteristic gas, as shown in Fig. 7. The peak value data of the gas concentrations in each group were statistically analyzed, as shown in Table 4. It can be seen that the VOC concentration changed significantly, whereas the concentrations of CO and H_2 hardly changed, and the VOC concentration curve increased significantly after 130 s, which means that in the overheating stage (early stage of fire development), the VOC concentration also increased significantly with the temperature. This also means that VOCs can be used as characteristic gases for cable early fire alarm and fire hazard detection.

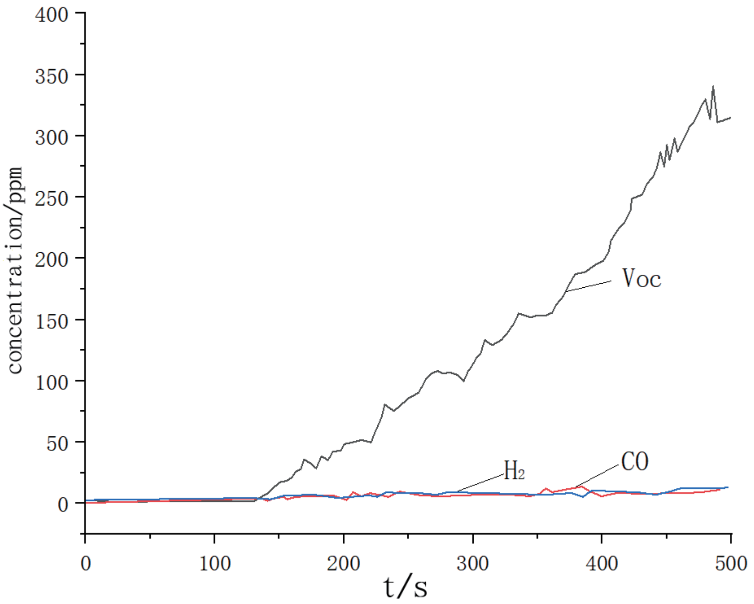


Fig. 7. (Color online) Concentration curve of each characteristic gas.

Table 4
Concentration of characteristic gas during cable overheating.

Concentration /ppm		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
CO	Average value (under normal condition	0.4	0.4	0.3	0.3	0.4	0.4
	Peak value (overheating)	0.6	0.7	0.9	0.5	0.8	0.5
H_2	Average value (under normal condition	0.1	0.1	0.1	0.2	0.1	0.1
	Peak value (overheating)	0.1	0.2	0.1	0.2	0.2	0.1
VOC	Average value (under normal condition	0	0	0	0	0	0
	Peak value (overheating)	375	336	351	348	362	356

3.3 Fire detection system in power cable tunnel

As the backbone of urban distribution networks, the safety of power cable tunnels is crucial. At present, many monitoring systems, including fire detection systems, have been built in cable tunnels.(26) A photograph of a power cable tunnel is shown in Fig. 8.

Currently, the fire alarm system of newly built power cable tunnels is composed of gas, temperature, and video sensors. Gas sensors include CO, Cl, HCl, CH_4, H_2S, and the other gas sensors installed on the wall of the tunnel. Optical fiber temperature sensors were attached to the cables. The video sensors were infrared cameras installed at the top of the tunnel.

These gas sensors are used to detect the decomposition products generated by the combustion of power cables. When a fire reaches the combustion stage, owing to the rapid development of power cable tunnel fires, even if these sensors provide fire alarms, it is often too late to take measures. Moreover, owing to the thick insulation layer of tunnel cables and various insulating materials in the tunnel, it is difficult for optical fiber temperature sensors and infrared cameras to detect fire hazards during the overheating stage of cables.

Therefore, to extinguish the fire in its early development stage, the proposed method based on pyrolytic particles and overheated characteristic gas monitoring can be adopted. By monitoring the nanoparticle count and VOC concentration in power cable tunnels, it is possible to identify potential fire hazards.

According to the above experimental data, at the beginning of a fire hazard, the number of nanoparticles and the concentration of VOCs increased, and their rising slopes also increased. Therefore, these two factors can be used as criteria for determining the existence of fire hazards.

To prevent interference and data acquisition errors in fire alarm applications, the trend value is used instead of the slope, and the trend value of the series contains the amount and direction of change, which can be obtained by a Kendall-τ trending algorithm:(27)

$$y(n)=\sum_{i=0}^{N-1}\sum_{j=0}^{N-1}u(x(n-i)-x(n-j)), \tag{1}$$

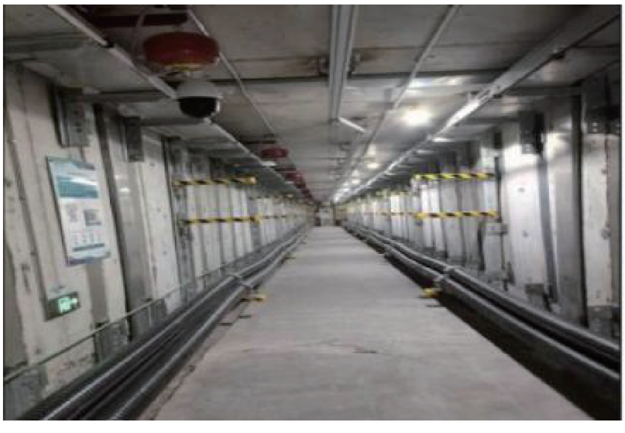


Fig. 8. (Color online) Photo of actual power cable tunnel.

where n is the discrete time variable, N is the length of the sensor data, and $u(x)$ is the unit-step function. Equation (1) can be modified as a recursive formula:

$$y(n)=y(n-1)+\sum_{i=0}^{N-1}\operatorname{sgn}(x(n)-x(n-i))-\sum_{i=0}^{N-1}\operatorname{sgn}(x(n-1-i)-x(n-N)). \tag{2}$$

Therefore, the trend values of the particle count and VOC concentration can be calculated using Eq. (2). The fire hazard logic is as follows:

$$\text{Alarm}(i)=\text{ Particle\_Alarm}(i)\ \ ||\ \ \text{VOC\_Alarm}(i). \tag{3}$$

Here,

$$\begin{aligned}\text{Particle\_Alarm}(i) = {} & (\text{Count}(i) > \text{TH\_COUNT })\\ & \&\&\ (\text{Count\_Trend}(i) > \text{TH\_COUNTTREND}),\end{aligned} \tag{4}$$

$$\text{VOC\_Alarm}(i) = (\text{VOC}(i) > \text{TH\_VOC }) \ \&\&\ (\text{VOC\_Trend}(i) > \text{TH\_VOCTREND}). \tag{5}$$

In the above equations, the threshold value of the particle count TH_COUNT, the threshold value of the particle count trend, the threshold value of the VOC concentration TH_COUNT, and the threshold value of the VOC concentration trend are set to empirical values based on actual site conditions.

Therefore, adding the fire hazard detection system proposed in this study to the existing power cable tunnel fire alarm system can better prevent the occurrence of fires and achieve good alarm effects.

4. Conclusions

To discover two common fire hazards (partial discharge and cable overheating) in power cable tunnels, two sets of experiments were designed. One was a partial discharge experiment for the epoxy resin and XLPE cables that are commonly used, and the other was a cable overheating experiment. In the two experiments, the counts of particles with different diameters generated at different stages of the experiment were observed, as well as the concentrations of common combustion gases. The experimental results show the following:

Nanoparticles were generated during the partial discharge experiment of the epoxy resin and XLPE cables. The total number of nanoparticles measured increased significantly with the discharge intensity. With the discharge intensity increasing, the corresponding concentration of VOCs also increased significantly.

In the heating experiment, the overheated cables emitted a large number of nanoparticles and the VOC concentration increased significantly. Therefore, for fire early alarming in power cable tunnels, we suggest that it is necessary to equip with particle counter devices to monitor the count of nanoparticles and with VOC sensors to monitor the VOC concentration. After obtaining the nanoparticle count and VOC concentration data, fire hazards can be detected in a timely manner to ensure the safe operation of power cable tunnels.

Acknowledgments

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