Numerical simulation research on the fire in cable cabin of utility tunnel with different longitudinal fire source locations

Dewang Geng, Bei Cao, Xiaodong Zhou, Hong Liu, Ziping Lu and Lizhong Yang

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui Province 230023, China

E-mail: yanglz@ustc.edu.cn

Abstract. A full-scale model was established by the Fire Dynamics Simulator (FDS) to study the fire characteristics in the cable cabin of utility tunnel with different longitudinal fire source locations. Five fire sources at different locations were placed in a 200-meter-long fire compartment. Several important parameters were obtained and analyzed, including temperature distribution, smoke concentration, and fire self-extinguishing. The results present that the fire source located at 1/2 of the longitudinal direction has the largest range of high-temperature smoke, which leads to the largest damage range of the concrete structure. The reverse filling of the smoke in the utility tunnel leads to the longitudinal CO peak concentration first decreasing and then increasing from the fire source to the end. When the fire source is located at 1/8 of the longitudinal direction, the fire self-extinguishing time is the longest. These encouraging results could provide significant references for the fire protection design and fire control of the utility tunnel.

1. Introduction
Utility tunnel is a special underground tunnel that provides transportation pipelines for urban public services. It is applied to integrate utility pipelines such as electricity, communication, fuel gas, heat supply, and water supply for unified planning, design, construction, and management [1]. With the utility tunnel being constructed rapidly, the fire protection problems in it are becoming increasingly prominent. These problems make the fire department and the municipal department encounter many difficulties in the acceptance and operation and maintenance of the utility tunnel’s construction. The inside of the utility tunnel contains power cables, communication cables, and gas pipelines, which have a high fire risk [2]. In addition, the underground utility tunnel has a service life of up to one hundred years. With the aging of pipelines and related equipment, the fire threat will become more serious [3-5].

Some scholars have carried out research on the fire safety of utility tunnel by experiments or simulations. Huang et al. analyzed the maximum ceiling temperature and longitudinal decay in a sealing tunnel fire by numerical simulations [6]. Ye et al. proposed a prediction method for the longitudinal maximum smoke temperature attenuation of ceiling jet flows generated by strong fire plumes in utility tunnel [7]. Zheng et al. explored a two-dimensional measurement method of fire smoke velocity field in utility tunnel based on the principle of Conservation of Optical Flow [8]. Mi et al. used simulation methods to explore the best smoke control mode for evacuation of people during the cable fire in utility tunnel by different ventilation methods, fire-proof doors, and sprinklers [9].
Most of the research only considered a single fire source location condition for the fire in the utility tunnel. It is more common to place the fire source in the middle of a fire compartment. However, the full-scale cable cabin fire experiment research has been involved rarely. As a typical sealed, narrow, and long underground structure, a single fire compartment of the utility tunnel can reach more than 200 m in longitudinal length. The fire may occur at different longitudinal locations in the utility tunnel. Considering the distribution of smoke and the spreading process of cable burning, it is meaningful to study the fire in the cable cabin of utility tunnel with different longitudinal fire source locations.

Therefore, to understand the fire of the utility tunnel under different locations, a full-scale utility tunnel model was established using the method of numerical simulation. The effects of different longitudinal fire source locations on utility tunnel are systematically investigated. Some important parameters such as the temperature distribution, the spreading process of cable burning, smoke concentration, as well as fire self-extinguishing are obtained and analyzed in detail. By studying the fire characteristics at different longitudinal fire sources in the cable cabin of the utility tunnel, the results can perfect the framework of the fire research of the utility tunnel and provide guidance for its fire protection design and fire control.

2. Numerical modeling

2.1. Physical model setup and simplify

It is well known that Computational Fluid Dynamics (CFD) is widely used to simulate different fire scenarios. Among them, the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology (NIST) has been verified by subsequent experiments, which has convincing simulation effectiveness [10-12]. Based on fluid dynamics theory, FDS can simulate building fires, tunnel fires, subway station fires, oil pool fires, and other fire scenarios.

Figure 1. Schematic diagram of the simplified cable model.

Figure 2. Cross-section diagram of the cable cabin.
In this paper, a 1:1 numerical model is established for analysis with a cable cabin of a utility tunnel in Baiyin City, Gansu Province, China as the research object. The model space has an internal clear width of 2.8 m, a clear height of 3.2 m, and a length of 200 m. Referring to the design drawings of the city's utility tunnel, the model is simplified within a reasonable range. The conductor covered in a common cable is three copper cores, the insulation material is cross-linked polyethylene (XLPE), filled with polyethylene (PE) foam, and the outermost layer is a polyvinyl chloride (PVC) sheath. This kind of power cable is generally used in the utility tunnel of many cities in China. In order to simplify the calculation of FDS, the main combustible material PVC of the cable is used as a simplified model of the cable, as shown in Figure 1. A total of 7 layers of cables are designed on the left and right sides in the cable cabin model of the utility tunnel, and the cross-section diagram is shown in Figure 2.

2.2. Simulation scenarios and settings

![Figure 3. Schematic diagram of the slices and measuring points (simulation scenario L5).](image)

This paper defines the model as the X-axis along the length, the Y-axis along the width, and the Z-axis along with the height. In order to study the influence of different longitudinal fire source locations on the fire in the cable cabin of the utility tunnel, the five fixed fire sources were set at X=1/25/50/75/100 m, which corresponded to the simulated scenarios L1/L2/L3/L4/L5. Recording previous studies and simulations on utility tunnel fires [13-15], this article used a stable fire source as a cable ignition device. The fire source of each simulation scenario was set at the bottom position on the left side of the cable cabin.

| Projects                  | Quantity      |
|---------------------------|---------------|
| Initial temperature       | 20 °C         |
| Initial pressure          | 101300 Pa     |
| Flooring material         | Concrete      |
| Ceiling material          | Concrete      |
| Cable ignition Temperature | 380 °C        |
| Cable heat release rate   | 265.0 kW/m²   |
| Simulation time           | 1200 s        |
Each simulation scenario has slices (temperature, smoke concentration and smoke visibility) located at $Y=1.4$ m, $Y=0.4$ m, $X=1/25/50/75/100$ m. In the case of $Y=0.4$ m or $Y=1.4$ m, the measuring points (temperature and smoke concentration) are arranged at an interval of 25 m along the X-axis at the height of 1.6 m and 3.1 m, as shown in Figure 3. The simulation parameters of the utility tunnel are shown in Table 1.

2.3. Mesh optimization
Since FDS uses the Courant–Friedrichs–Lewy (CFL) condition, calculation parameters such as time steps are controlled by mesh accuracy. According to the sensitivity requirement formula of McGrattan et al. [16], the accuracy of the mesh depends on the power of the fire source. The calculation formula is as follows:

$$D^* = \left(\frac{\hat{Q}}{\rho_a c_a T_a g}\right)^{2/5}$$

(1)

where $D^*$ represents the fire characteristic diameter, $\hat{Q}$ represents the heat release rate of fire source (kW), $\rho_a$ represents the air density ($1.2$ kg/m$^3$), $c_a$ represents heat release the specific heat capacity of air ($1.014$ kJ/(kg·K)), $T_a$ represents the air temperature ($293$ K), and $g$ represents the acceleration of gravity ($9.81$ m/s$^2$). When the mesh size is set as 1/4-1/16 of the fire characteristic diameter, the simulation results are relatively accurate [17]. By (1), the characteristic diameter of the fire source is calculated as $1.26$ m. Taking into account the computer's data processing capabilities, it is hard to make the calculation with small mesh sizes. Meanwhile, the coarse mesh size affects the accuracy of the simulation results. Considering the performance of the computer and the accuracy of the simulation results, this study selects mesh sizes of $0.13-0.2$ m for comparison and analysis. The simulations of different mesh sizes use simulation scenario L5, and temperature slice 2 ($Y=0.4$ m) is used to extract temperature values at the same height (3.2 m). The temperature at different horizontal distances from the fire source is selected for comparison. The results are shown in Figure 4. The mesh size of 0.16 m meets the accuracy requirements of the simulation results better [9, 18]. Therefore, the following five simulation scenarios in this article are analyzed with a mesh size of 0.16 m.

Figure 4. The temperature distribution at different horizontal distances from the fire source (simulation scenario L5).

3. Results and discussions

3.1. Temperature distribution and attenuation
The outer wall of the model selected in this paper is a concrete structure. The compressive strength of concrete under a high temperature is the main basis for judging the damage degree of the utility tunnel structure after a fire, which plays an important role in judging the safety of the structure. Therefore,
this paper takes the compressive strength of concrete as the basic parameter to determine the degree of concrete damage. Predecessors have done a lot of researches on the compressive strength of concrete at high temperatures [19]. When the temperature is lower than 300 °C, the compressive strength of concrete is close to the normal value. When the temperature reaches 300 °C, the compressive strength of concrete begins to decrease. As a result, the following uses 300 °C as the critical temperature condition to evaluate the high-temperature damage of the concrete structure. It is considered that the concrete structure begins to be damaged after the temperature reaches 300 °C.

Through the simulation results, it can be found that the high-temperature smoke distribution reaches the maximum range at the moment of the peak heat release rate of the fire. Then the heat release rate of the cable fire begins to decrease, and the range of high-temperature smoke gradually shrinks until the fire self-extinguishes due to lack of oxygen. The temperature slice 2 (Y=0.4 m) at the fire source is selected to draw Figure 5, which shows the longitudinal temperature distribution of the five simulated scenarios when the fire heat release rate reaches the peak. Due to the layered arrangement of the cables, it can be seen that the distribution of the smoke temperature also presents the characteristics of layering. Moreover, there are significant differences in the longitudinal temperature distribution of the five simulated scenarios. As the location of the fire source changes from the end to the middle of the cable cabin, the temperature distribution range above 300 °C gradually becomes larger. In other words, simulated scenario L1 has the smallest damage range of the concrete structure. Simulated scenario L5 has the largest damage range of the concrete structure, whose high-temperature smoke range above 300 °C can reach 156.8 m (78.4 %) in the longitudinal section.

![Figure 5. Contours of longitudinal temperature distribution (Y=0.4 m).](image)

It can be known from the simulation results that during the development stage of cable fire, the temperature at the fire source reaches its peak and remains almost stable. Therefore, the average temperature longitudinal attenuation curve of the ceiling of the utility tunnel at this stage is drawn as shown in Figure 6(a). According to the peak temperature at each temperature measurement point, the
maximum temperature longitudinal attenuation curve of the ceiling in five simulation scenarios is drawn as shown in Figure 6(b). As the distance from the fire source increases, it shows an exponential decay trend. When the space on both sides of the fire source is symmetrical, the temperature longitudinal attenuation curve is axisymmetric. At the same height where the temperature measuring points are arranged, the maximum temperature appeared at the fire source, especially the peak temperature of simulated scenario L4 reached 961 °C. In the case of the temperature longitudinal attenuation conforming to the exponential law, a temperature measurement point value (X=25 m) of the simulated scenario L1 has obvious fluctuations. This is because the fire source of this simulated scenario is close to the end, where the oxygen concentration around the fire source is relatively low. This condition causes a phenomenon of ghosting fire as shown in Figure 6(b) [20-22]. Therefore, the ghosting fire affects the value of the temperature measurement point near the fire source, resulting in a deviation that is inconsistent with the exponential law. Actually, in the five simulation scenarios, flames ghosted in the later stage of the cable fire, especially the simulation scenario L1 was the most obvious.

3.2. Cable fire spreading process
The results show that the process of cable fire spreading at the cross-section of the fire source is the same in the five simulation scenarios. The bottom cable on the left starts to catch fire, which causes the flame to spread upward to other cables on this side. As the flame propagates upward, it spreads outward under the influence of the upper cable at the same time. The extension of the flame ignites the cable on the right. However, the burning range of the right cable is significantly smaller than that of the left cable where the fire source is located. When the uppermost cable on the left is ignited, the flame spreads along with the ceiling of the cable cabin to the opposite side, thereby intensifying the burning of the uppermost cable on the right. Eventually, all the cables on the right began to burn violently. During the whole process, all the cables on the left and right sides were ignited. Especially the flame of the cable on the left side where the fire source was located had a longer spreading range in the longitudinal direction.

Figure 7. Contours of cross-section temperature distribution at fire source (X=1/25/50/75/100 m).
The temperature slice 3 (X=1/25/50/75/100 m) at the fire source is selected to draw Figure 7, which shows the cross-section temperature distribution of the five simulated scenarios when the fire heat release rate reaches the peak. It can be seen that the temperature near the fire source can reach 980 °C or even above. The area on the left has the highest average temperature, followed by the area on the right and the ceiling of the cable cabin. On the cross-section of the fire source, the simulation scenario L2 has the smallest high-temperature distribution range. The simulation scenario L5 has the largest high-temperature distribution range, which has far exceeded the critical temperature value of concrete structure damage.

### 3.3. Distribution of smoke concentration

Fire smoke has three main hazards: (1) High-temperature smoke carries and radiates a large amount of heat; (2) The oxygen content in the smoke is low, forming an oxygen-deficient environment; (3) The smoke contains certain toxic components and is harmful ingredients, corrosive ingredients, particulate matter, etc. It is known that CO is the most decisive hazardous gas in the smoke produced by a fire.

From the simulation results, the CO concentration at the fire source is relatively stable during the development stage of cable fire. Therefore, the average CO concentration curve of the utility tunnel at this stage is drawn as shown in Figure 8(a). According to the CO peak concentration at each smoke measurement point, the maximum CO concentration curve of the utility tunnel in five simulation scenarios is drawn as shown in Figure 8(b). It can be seen from Figure 8(a) that the average CO concentration of simulated scenarios L2-L5 near the fire source is relatively low, which means the farther away from the fire source, the higher the average CO concentration can be. Among them, the minimum average CO concentration of the simulated scenarios L2 and L3 did not appear at the fire source. This is because the fire source in these scenarios is close to the end, making the space filled by the fire smoke on both sides is asymmetrical. In the smaller side space, the smoke is affected by buoyancy and spreads along with the ceiling to the end. Then the smoke cools and sinks to the bottom of the utility tunnel, filling to fire source in the opposite direction, which causes an increase in the average CO concentration at the fire source. The fire source of simulated scenario L1 is located at one end of the entire fire compartment model, and the fire development space has only one direction. There is no obvious reverse filling of the smoke spreading, which can also explain that the average CO concentration distribution curve of the simulated scenario L1 is the most special. Meanwhile, it can be seen from Figure 8(b) that the maximum CO concentration curves of the five simulation scenarios show a consistent law. The CO peak concentrations at the fire source can reach the maximum value, and the CO peak concentrations at the end position can also reach a relatively larger value. In particular, the CO peak concentrations of the simulated scenarios L1 and L3 can reach 305-309 ppm. The CO peak concentrations along the longitudinal direction first decrease and then increase from the fire source to the end. Therefore, the CO concentration curve at different horizontal distances from the fire source shows a "W" pattern, which is also related to the reverse filling of the smoke after spreading along with the ceiling to the end.

Similarly, the average oxygen concentration curve of the utility tunnel at the development stage of cable fire is drawn as shown in Figure 9(a). According to the oxygen valley concentration at each smoke measurement point, the minimum oxygen concentration curve of the utility tunnel in five simulation scenarios is drawn as shown in Figure 9(b). It can be seen from Figure 9(a) that the average oxygen concentration of simulated scenarios L2-L5 near the fire source is relatively high, which is contrary to the distribution law of average CO concentration. Meanwhile, it can be seen from Figure 9(b) that the minimum oxygen concentration curves of the five simulation scenarios show a consistent law. And the oxygen valley concentration of the simulated scenarios L1 and L3 can reach 0.038-0.039 mol/mol. The minimum oxygen concentration curve along the longitudinal direction shows an "M" pattern.
3.4. Fire self-extinguishing

In order to compare the fire self-extinguishing laws of the five simulation scenarios, the oxygen concentration measurement points at the fire source location are selected. The curves diagram of the fire extinguishing oxygen concentration and time is drawn, as shown in Figure 10. It can be seen that the fire self-extinguishing oxygen concentration of simulation scenario L1 is the minimum, which can reach about 0.061 mol/mol. As the location of the fire source changes to the middle of the cable cabin, the self-extinguishing oxygen concentration of the fire gradually rises. And the fire self-extinguishing oxygen concentration of simulation scenario L5 is the maximum, which can reach about 0.107 mol/mol. Meanwhile, the fire self-extinguishing time of simulation scenario L2 is the longest. The oxygen supplement conditions in the simulation scenarios L4 and L5 are better, making the cable burnt relatively fully, accelerating the fire development process. That is why their self-extinguishing time is earlier. Moreover, the fire self-extinguishing time of the simulated scenario L1 is relatively earlier than the simulated scenario L2. This is because the high-pressure smoke close to the end obstructs the flow of air to the fire source, which leads to the pollution of the combustion environment around the fire source, accelerating the self-extinguishing of the fire.
Figure 10. Curves of self-extinguishing oxygen concentration and self-extinguishing time in different simulation scenarios.

4. Conclusions
This study explored the fire characteristics and differences in cable cabins of the utility tunnel at different longitudinal fire sources through numerical simulation methods. The fire simulated scenarios of the utility tunnel were characterized by temperature, smoke concentration, and fire self-extinguishing. The main conclusions can be summarized as follows:

(1) When the fire source is located at 1/2 of the longitudinal direction, the range of high-temperature smoke is the largest, which can reach 78.4% of the longitudinal length of the utility tunnel. In this case, the damage range of the concrete structure is also the largest. The longitudinal attenuation of the cable cabin ceiling temperature conforms to the exponential law. However, when the space on both sides of the fire source is asymmetric, the ghosting fire affects the temperature distribution near the fire source.

(2) The reverse filling of the smoke in the utility tunnel affects the distribution of CO concentration. In the case of the fire source being located at different locations, the CO peak concentration along the longitudinal direction first decreases and then increases from the fire source to the end.

(3) Longitudinal fire source location has a significant effect on fire self-extinguishing. As the location of the fire source changes to the middle of the cable cabin, the self-extinguishing oxygen concentration of the fire gradually rises. When the fire source is located at 1/8 of the longitudinal direction, the fire self-extinguishing time is the longest.

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