Study on the Smoke Spread Law of a Subway Tunnel Fire under the Synergistic Action of Shaft Smoke Exhaust and Longitudinal Ventilation

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Abstract. Urban rail transit improves the urban spatial structure, solves the problem of urban traffic congestion, so its safety problem can not be ignored. Fire is one of the major factors threatening the safety of urban rail transit. Taking the tunnel between wengjiao road and Maqing road of Xiamen Rail Transit Line 2 as an example, the paper uses FDS software to simulate the mechanical smoke exhaust of the shaft under different wind speed conditions of the main tunnel, and deeply analyzes the smoke and temperature distribution under the fire conditions of the tunnel with the shaft. The results show that when the longitudinal wind speed $v=1.7m/s$ and the shaft uses mechanical exhaust, there is no smoke upstream of the fire source, all the smoke is discharged through the shaft, and the height of the flue gas layer is significantly smaller than the thickness of the flue gas layer without longitudinal ventilation. The combination of longitudinal wind and mechanical smoke exhaust is more conducive to the safe evacuation of people.

1. Introduction

Fire is one of the main factors threatening the safety of the tunnel (see Figure 1). For example, the French Mont Blanc Tunnel and the British Channel Tunnel fire caused huge casualties. Studying the law of fire smoke generation and spread, the control strategies of fire smoke, and the characteristics and difficulties of emergency evacuation of tunnel fires have important practical significance for the design and rescue evacuation of tunnel fire safety systems. A lot of researches on tunnel fire have been carried out at home and abroad. Palazzi et al. [1] conducted a theoretical study on the tunnel with slope, and analyzed the influence of slope on critical wind speed and the interaction between fire source and flue gas. Tao Gang et al. [2] performed numerical simulation analysis using numerical simulation software and found that the slope of the tunnel has an important influence on the smoke flow and the critical wind speed of the tunnel fire in the subway section. Bettis et al. [3, 4] carried out the full-scale tunnel fire test, and found that the critical wind speed changes with its 1/3 power when the heat release rate of the fire source is low, but when the heat release rate increases to a certain amount, to a large extent, the critical wind speed does not change. Li et al. [5, 6] obtained the theoretical calculation
model of the maximum flue gas temperature of tunnel fire through theoretical analysis, and verified it with experimental data. Ding Houcheng et al. [7] analyzed the characteristics of fire smoke flow when the doors on both sides of the train were opened simultaneously and the doors on one side were opened. Fan Yiteng et al. [8] studied the temperature distribution and flow characteristics of smoke at the top of the two-point smoke exhaust system in a long tunnel fire. Xu Pai et al. [9] established the theoretical prediction model of the relationship between the parameters of smoke exhaust valve and the air pressure of smoke exhaust fan under the uniform smoke exhaust mode, and obtained the analytical solution. In this paper, the numerical simulation method is used to study the smoke spreading law, temperature field distribution characteristics and longitudinal smoke exhaust efficiency. The research results can be used as an important reference for the disaster prevention design and operation of long and large tunnels in mountainous areas.

![Figure 1. Tunnel fire](image1)

### 2. Numerical model

In this paper, the tunnel between wengjiao road and Maqing road of Xiamen Rail Transit Line 2 is taken as the research object. Through the numerical calculation software, the smoke diffusion and temperature field distribution in the case of fire in the tunnel are simulated. The smoke distribution under different working conditions is obtained by changing the longitudinal ventilation speed. The tunnel is a double hole single track saddle type. Because the length of the tunnel is long, the establishment of a real tunnel will greatly increase the number of FDS grids, resulting in the calculation time is too long. Therefore, this paper only intercepts a section of interval tunnel for corresponding simulation, and establishes a model tunnel after appropriate simplification. The model tunnel is 400m long, 5.4m wide and 5.2m high (see Figure 2).

![Figure 2. Tunnel cross section](image2)

In practical engineering, the method of vertical shaft combined with longitudinal ventilation is often used to study the smoke exhaust of tunnel fire. There is a shaft on the top of the tunnel as a vent, so as to effectively and quickly smoke exhaust. Based on this, the actual engineering drawing is simplified, and the smoke exhaust channel with a shaft on the top of the tunnel is established. The position of the shaft is directly connected with the tunnel, the shaft size is 5m×4m×35m, and the center of the shaft is about 70m away from the center of the tunnel (see Figure 3).
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In this paper, the smoke exhaust effect of tunnel fire under the synergistic effect of shaft smoke exhaust and longitudinal ventilation is discussed. Therefore, in the design of working conditions, 400m is used as the length of the basic tunnel model, and a standard B-type train model is set in the middle of the tunnel. The fire source is attached to the upper part of the middle of the train (the middle of the tunnel). The cross-sectional area of the fire source is 3m$^2$, and the power of the fire source remains unchanged, which is 7.5MW.

When adding shaft model and FDS numerical calculation, it is necessary to mesh the shaft. Because the power of the fire source remains unchanged, the grid of 0.5m×0.5m×0.5m can be used for the grid division of the shaft model, and in order to calculate quickly, the multi-stage grid division is adopted, with a total number of 125000 grids.

3. Result analysis
In the actual project, the shaft shall be set with relevant smoke exhaust volume to conduct the smoke exhaust research under the dual effect of combined with longitudinal ventilation (see Figure 4).

\[ M = 0.07Q_{c}^{1/3}Z^{3/5} + 0.0018Q_{c} \]  \hspace{1cm} (1)

\[ M = 0.032Q_{c}^{3/5}Z \]  \hspace{1cm} (2)

Where: $Q_{c}$ is the fire heat release(kW); $Z$ is the height from the combustion surface to the ceiling(m); $Z_{l}$ is the limit height of the fire source(m).

\[ Z_{l} = 0.166Q_{c}^{2/5} \]  \hspace{1cm} (3)

Therefore, the volume smoke production is:

\[ V = MT_{v}/\rho_{0}T_{0} \]  \hspace{1cm} (4)

\[ T_{v} = Q_{c}/MC_{p} + T_{0} \]  \hspace{1cm} (5)

According to the above formula, and considering the fresh air mixing amount, in case of a 7.5MW fire in the tunnel, the smoke exhaust amount required for the shaft is 66m$^3$/s, and the calculation results are compared with the relevant reference table (see Table 1), meeting the standard.
Table 1. Smoke exhaust capacity of different smoke exhaust methods

| Smoke heat release rate (MW) | 20  | 30  | 50  |
|-----------------------------|-----|-----|-----|
| Smoke generation rate (m³/s) | 100–120 | 120–150 | 150–200 |

Combined with the above analysis, in this paper, when there is a shaft as a smoke outlet, 66 m³/s mechanical smoke exhaust combined with longitudinal wind is used for smoke exhaust.

In this paper, the main tunnel adopts 0m/s, 1.1m/s and 1.7m/s longitudinal ventilation respectively, and the shaft adopts 66m³/s mechanical smoke exhaust mode to carry out the numerical simulation of fire smoke exhaust effect.

3.1. Calculation results under the condition that the main tunnel is not ventilated and the shaft adopts 66 m³/s smoke discharge

The smoke spread effect diagram of the model at different times is shown in Figure 5. It can be seen from the above that when the fire occurs for about 100s, all the flue gas downstream of the fire is discharged through the shaft. Due to the function of the shaft, the flue gas spread distance at the upstream of the fire source is greatly reduced. With the continuous combustion, all the flue gas downstream of the fire source is discharged through the shaft, and there is no flue gas at the downstream of the shaft. The flue gas upstream of the fire source is discharged through the tunnel portal, and when the fire occurs for 550s, the flue gas is distributed the upstream position of the whole tunnel is full, and after that, it is basically unchanged.

![Figure 5. Tunnel smoke spread at different times](image)

As the main tunnel is the direct way to evacuate people, it is necessary to analyze the temperature change of the tunnel section (see Figure 6).

![Figure 6. Distribution of longitudinal temperature in tunnel at different time](image)

In order to further analyze the safety critical conditions for the evacuation of people in the tunnel, this paper makes statistics and analysis on the distribution of flue gas components (temperature, visibility, CO volume fraction) along the tunnel 1.85m away from the tunnel (see Figure 7).
As shown in Figure 7, when the main tunnel is not ventilated and the shaft adopts 66 m$^3$/s mechanical smoke exhaust, the change of flue gas composition along the critical height of the main tunnel ($z=1.85$m) is as follows:

The maximum temperature of the tunnel ceiling near the fire source has little change. The temperature of the tunnel ceiling at the downstream of the fire source only exists in the area from the center of the fire source to the opening of the shaft, and there is no smoke at the downstream of the shaft. When the fire source burns stably, the temperature of the tunnel ceiling at the upstream of the fire source decreases linearly with the increase of the distance from the center of the fire source, and the temperature of the tunnel ceiling at the opening of the tunnel at the upstream of the fire source is about 29℃, the temperature at the opening of the tunnel is significantly lower than that of the shaft without mechanical exhaust, indicating that the temperature of the ceiling in the tunnel is significantly reduced by mechanical exhaust.

At the critical height of the tunnel, since all the downstream of the fire source is discharged from the vertical wellhead, only the flue gas content near the shaft is monitored at the downstream of the fire source. The flue gas temperature is about 27℃, the visibility is 6.5m, and the volume fraction of CO is 15ppm. The smoke in the upstream of the fire source spreads in the tunnel. Because the flue gas in the upstream of the fire source settles to the critical height, the content of flue gas is relatively low, and the impact on evacuation is relatively low in a short time.

3.2. Calculation results under the condition that the vertical wind speed is 1.1 m/s and the shaft adopts 66 m$^3$/s smoke discharge

The smoke spread effect diagram of the model at different times is shown in Figure 8. It can be seen from the above that when the fire occurs for about 100s, the distance of smoke spreading to the upstream of the fire source is significantly smaller than that without mechanical ventilation. After 200s of fire, due to the maximum heat release rate of the fire source, the flue gas content gradually increases, and the "suction" generated by mechanical ventilation is not enough to ensure that the flue gas does not move to the downstream of the fire source. When the fire occurs 300s later, the flue gas spreads to the opening at the upstream of the fire source, and due to the mechanical exhaust effect of the shaft, all the flue gas at the downstream of the fire source is discharged through the shaft, and there is basically no flue gas at the downstream of the shaft.

Figure 8. Tunnel smoke spread at different times
As the main tunnel is the direct way to evacuate people, it is necessary to analyze the temperature change of the tunnel section (see Figure 9).

![Temperature Distribution in Tunnel](image1)

**Figure 9.** Distribution of longitudinal temperature in tunnel at different time

In order to further analyze the safety critical conditions for the evacuation of people in the tunnel, this paper makes statistics and analysis on the distribution of flue gas components (temperature, visibility, CO volume fraction) along the tunnel 1.85m away from the tunnel (see Figure 10).

![Flue Gas Composition Distribution](image2)

**Figure 10.** Distribution of flue gas composition in longitudinal line of tunnel

As shown in Figure 10, when the main tunnel adopts 1.1m/s longitudinal ventilation and the shaft adopts 66m³/s mechanical smoke exhaust, the variation of flue gas composition along the critical height of the main tunnel (z=1.85m) is as follows:
The maximum temperature of the tunnel ceiling near the fire source basically changes little. The upstream flue gas countercurrent distance of the fire source is about 40m. Due to the synergistic effect of the longitudinal wind and mechanical smoke exhaust, the flue gas is blown to the downstream direction of the fire source by the longitudinal wind, and discharged through the mechanical smoke exhaust of the shaft. At the same time, there is no flue gas at the downstream of the shaft. The smoke generated by the fire is all discharged through the opening of the shaft, and some smoke still exists upstream of the fire source. the composition of flue gas at z=1.85m is low, the maximum temperature is less than 30℃, the visibility of flue gas is not less than 13m, and the volume fraction of CO is not more than 8ppm.
3.3. Calculation results under the condition that the vertical wind speed is 1.7m/s and the shaft adopts 66 m$^3$/s smoke discharge

The smoke spread effect diagram of the model at different times is shown in Figure 11. It can be seen that the process of smoke spread caused by fire is basically similar to that of small wind speed. There is no smoke above the fire source, indicating that the longitudinal wind speed of 1.7m/s has reached the critical wind speed, and the thickness of smoke layer produced by the fire is very low.

![Figure 11. Tunnel smoke spread at different times](image)

As the main tunnel is the direct way to evacuate people, it is necessary to analyze the temperature change of the tunnel section (see Figure 12).

![Figure 12. Distribution of longitudinal temperature in tunnel at different time](image)

In order to further analyze the safety critical conditions for the evacuation of people in the tunnel, this paper makes statistics and analysis on the distribution of flue gas components (temperature, visibility, CO volume fraction) along the tunnel 1.85m away from the tunnel (see Figure 13).

![Figure 13. Distribution of flue gas composition in longitudinal line of tunnel](image)
As shown in Figure 13, when the main tunnel adopts 1.7m/s longitudinal ventilation and the shaft adopts 66m$^3$/s mechanical smoke exhaust, the change of flue gas composition along the critical height of the main tunnel ($z$=1.85m) is as follows:

The maximum temperature of tunnel ceiling near the fire source is significantly lower than that of the smaller wind speed. The maximum temperature is about 800$^\circ$C, and the flue gas temperature at the upstream of the fire source is basically the initial temperature, which indicates that the wind speed has reached the critical wind speed requirements. Due to the collaborative use of longitudinal wind and mechanical smoke exhaust, the flue gas at the downstream of the fire source is discharged from the shaft.

Due to the synergistic effect of longitudinal wind and mechanical smoke exhaust, the smoke produced by the fire basically subsides in a large amount and accumulates at the junction of the shaft as much as possible. Among them, the smoke content at the critical height near the shaft slightly increases, but the increase is relatively low. The temperature of the smoke is about 33$^\circ$C, the visibility of the smoke is about 5m, and the volume fraction of CO is about 15ppm, showing a low level in general.

4. Conclusions

In this paper, the numerical simulation is carried out under the condition that the fire point of the train is in the middle of the tunnel and there is a shaft in the tunnel for mechanical smoke exhaust. The following conclusions are drawn:

When the tunnel is naturally ventilated, all the downstream flue gas is discharged through the shaft. The ceiling temperature of the tunnel opening at the upstream of the fire source is about 29$^\circ$C, which is significantly lower than that of the shaft without mechanical smoke extraction, indicating that the use of mechanical smoke extraction significantly reduces the temperature of the tunnel ceiling.

When the vertical wind speed $v$=1.7m/s, the height of the flue gas layer is significantly smaller than the thickness of the flue gas layer without longitudinal ventilation. At this time, the critical wind speed has been reached, the flue gas temperature is about 33$^\circ$C, the flue gas visibility is about 5m and the CO volume fraction is about 15 ppm, which is overall low.

Therefore, the combination of longitudinal wind and mechanical smoke exhaust is conducive to the safe evacuation of personnel. The results show that the combined effect of longitudinal ventilation and shaft mechanical smoke exhaust can be used in tunnel fire smoke control.

5. References

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