Study on smoke exhaust by roof openings in an underground fire lane

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Abstract. To discuss the natural ventilation design parameters of underground fire lane for underground metro depot, a series of numerical simulations were conducted in this study to investigate the influence of opening interval on the smoke exhaust based on an underground fire lane of Chongqing Metro. The results indicated that: (1) Reducing the opening interval resulted in a decrease in both the spread distance of smoke and the speed at which the smoke front propagated. (2) The change in the opening interval did not significantly affect the distribution of ceiling temperatures between the fire source and the roof opening. However, decreasing the opening interval led to a reduction in the range of the high-temperature area on the ceiling. (3) While the increase in the opening interval did not have a notable effect on the visibility distribution near the fire source, it did increase the overall visibility behind the opening. The research outcomes presented in this paper offer valuable insights for the design of ventilation systems in underground fire lanes in the future.

Keywords: Metro depot, Underground fire lane, Natural ventilation, Opening interval.

1 Introduction

With the ongoing process of urbanization, the significance of rail transit systems has been steadily increasing, leading to a rise in the number of individuals opting for subway travel. To ensure the smooth operation of subway vehicles along the subway lines, it is essential to have one or two subway depots allocated to each line. Given the rapid expansion of China's urban rail transit network, the number of subway depots in mainland China has exceeded 300 by the end of 2020 [1]. These depots typically occupy substantial land areas, with low building density. In light of the escalating scarcity of urban land resources, it has become imperative to adopt a comprehensive approach to the development of subway depots, focusing on land resource conservation. Consequently, an increasing number of subway depots are being constructed underground, with commercial buildings or parks situated above ground level. While this

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strategy effectively maximizes land utilization, it also introduces heightened security risks.

Due to the fire risk associated with underground metro depots, the construction of underground fire lanes becomes necessary to facilitate timely firefighting and rescue operations. However, it is important to acknowledge that underground fire lanes also pose their own fire risks [2]. To ensure the protection of tunnel structures and the safe evacuation of personnel in the event of a fire, the implementation of an effective ventilation system is crucial. Currently, there is no national standard available as a reference for establishing such a system in underground fire lanes. Given the structural considerations of the area above the underground fire lane, natural ventilation emerges as a favorable option. Natural ventilation is a topic of interest among scholars due to its energy efficiency and ease of maintenance.

Extensive research has been conducted on natural ventilation in road tunnels or subway tunnels by various scholars. Yan et al. [3] conducted full-scale experiments and verified that a vertical shaft effectively exhausts a significant amount of smoke and heat, ensuring the safety of the tunnel. Wang et al. [4] conducted full-scale experiments and CFD simulations to investigate the fire characteristics in a naturally ventilated tunnel with roof openings. The study revealed that most of the smoke can be directly exhausted through the roof openings, thereby reducing the smoke content in the tunnel. Ura et al. [5] utilized a 1/12 scale model tunnel to investigate whether natural ventilation with roof openings can effectively maintain tunnel safety during a fire incident. The study demonstrated that the smoke spread distance is unrelated to the heat release rate, and roof openings cause the smoke layer height in the tunnel to rise rapidly. He et al. [6] investigated smoke exhaust in a subway tunnel under natural ventilation with a wide roof opening (equal to tunnel's width) using a 1/10 scale model tunnel. The results indicated that there is a critical opening longitudinal length that allows for complete smoke exhaustion under fire conditions. Yao et al. [7] studied the influence of shaft interval on smoke exhaust using numerical simulations. The results showed that, for a given shaft length, the total smoke spread length increases with the dimensionless shaft interval.

However, the study of natural ventilation in underground fire lanes remains limited. Xie et al. [8] used CFD software to study the effects of opening ratio on the smoke exhaust of the underground fire lane. The results show that increasing the opening ratio can effectively reduce the non-dimensional temperature rise value and smoke speed of the fire lane, meanwhile improve the visibility and smoke layer height in the lane. Liu et al. [2] conducted a full-scale experiment to analyze the minimum clear height of underground fire lane, and the experiment results show that the lower edge of the smoke layer is kept at a height of 5m and remains stable.

It is important to note that underground fire lanes differ significantly from road tunnels and subway tunnels in terms of structure, rendering the research findings non-transferable. Presently, no studies have explored the impact of opening interval on natural smoke exhaust in underground fire lanes. The selection of opening interval plays a pivotal role in the design of a natural ventilation system for such fire lanes, as it directly influences the effectiveness of natural smoke exhaust. Consequently, to provide more comprehensive guidance for real-world projects, an investigation into the influence of opening interval on the natural smoke exhaust in underground fire lanes becomes imperative. This study aims to investigate the influence of opening intervals on natural smoke exhaust based on a practical project involving an underground fire lane.

2 Numerical Simulation

In this paper, the influence of opening intervals on natural smoke exhaust in underground fire lanes is studied using Fire Dynamic Simulator (FDS) 6.7.0 [9]. FDS is a software tool commonly employed for simulating fire scenarios and has found extensive application in the field of fire safety.

2.1 Tunnel Model in FDS

A full-scale underground fire lane was constructed in FDS based on a metro depot in Chongqing, as depicted in Figure 1. The tunnel had three sides with lengths of 240 m, 60 m, and 240 m, respectively. The cross-section dimensions of the tunnel were 5 m in width and 5.5 m in height. The width of the roof opening was fixed at 4 m, while the opening interval was varied while maintaining a constant total opening area. Specifically, the opening spacing configurations were set at 30 m, 40 m, 50 m, 60 m, and 70 m. In all simulation scenarios, the fire source was positioned at the center of all roof openings, with a fixed heat release rate of 5 MW. The opening arrangement and the location of the fire source are shown in Figure 2.

The wall material of the bifurcated tunnel was set as "CONCRETE". Both the entrance and the exit were set as "OPEN". The ambient temperature was 20°C, the pressure was set to 101325.0 Pa, and the total simulation time was 600 s. The detailed simulation conditions are summarized in Table 1.

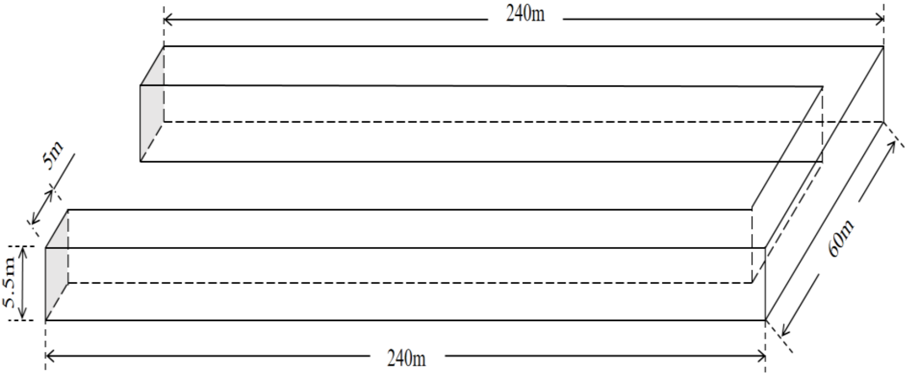

Fig. 1. Schematic view of the model tunnel.

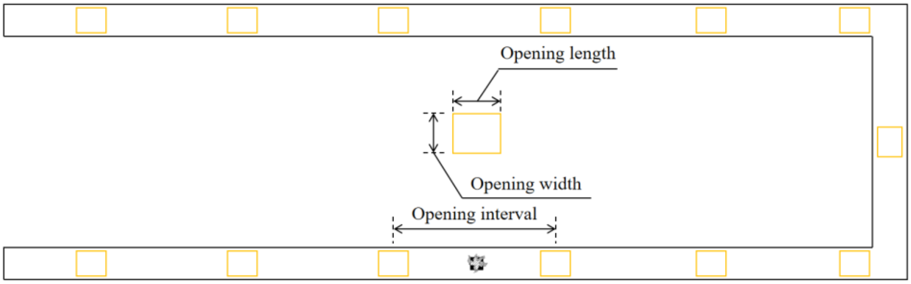

Fig. 2. Schematic view of opening arrangement and fire location.

Table 1. Summary of the FDS simulation cases.

Case No.	HRR(MW)	Total opening area(m^2)	Opening number	Opening width(m)	Opening interval
A1-A5	5	265	17,13,10,9,8	4	30m,40m,50m,60m, 70m

2.2 Meshes

The grid size δx determines the accuracy of the simulation and the simulation time. The grid size δx is recommended in the range of 0.0625 D^* ~ 0.25 D^* [10]. The characteristic diameter of the fire source D^* (m) can be calculated by:

$$D^* = \left(\frac{Q}{\rho_a C_p T_a g^{\frac{1}{2}}}\right)^{\frac{2}{5}} \quad (1)$$

Previous study has shown that good agreement between simulations and tests can be achieved when the grid size equals to 0.1 D^* [11]. Therefore, the mesh size of all simulations in this paper is set to 0.1 D^*, equivalent to 0.18m.

2.3 Validation

To validate the accuracy of FDS for underground fire lanes, a comparison was conducted between the FDS data and the results of small-scale experiments reported by Lu et al. [12]. A small-scale tunnel model was created in FDS, mirroring the dimensions, wall materials, and other conditions of the small-scale model tunnel used in Lu et al.'s experiments [12]. Three numerical simulation schemes, labeled as F1-F3, were performed to correspond to the experimental scenarios S1-S3 outlined in Lu's study. The comparison between the numerical simulation results and the small-scale experiments is presented in Figure 3. It can be observed that the temperature calculated by FDS closely aligns with the temperature measured in the small-scale experiments. The majority of data points deviate by less than 15% from the equality line. Hence, the application of FDS for further research is considered both reasonable and reliable.

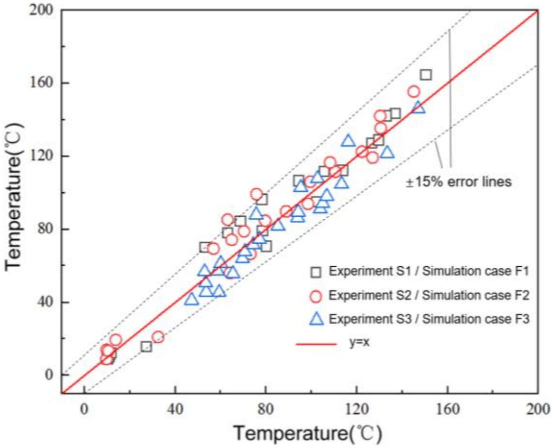

Fig. 3. Experimental values compared to the FDS data.

3 Results and Discussion

3.1 Effect of Opening Interval on Smoke Diffusion

Figure 4 illustrates the impact of opening intervals on the total smoke spread distance on both sides of the fire source. As depicted in Figure 4, the smoke spread distance increases as the opening interval widens. When the opening interval is set at 30 m, the smoke spread distance remains around 85 m. However, when the opening interval is increased to 40 m, the smoke spread distance exceeds 100 m. These results indicate that reducing the opening interval is beneficial for confining the smoke within a smaller range.

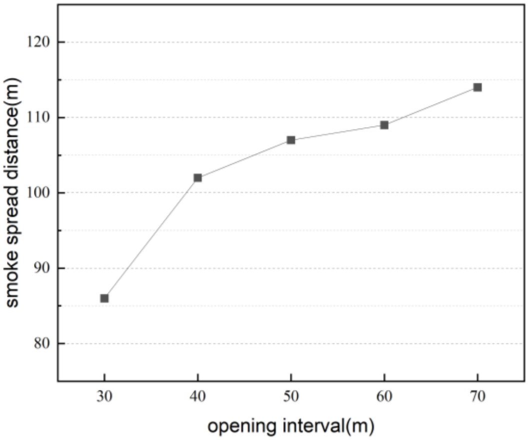

Fig. 4. Smoke spread distance under different opening intervals.

Figure 5 presents the time taken for the smoke front to reach different positions along the tunnel under varying opening intervals. It can be observed from Figure 5 that as the opening interval decreases, the time required for the smoke front to reach the same distance from the fire source increases. This indicates a decrease in the smoke spread speed with a reduction in the opening interval.

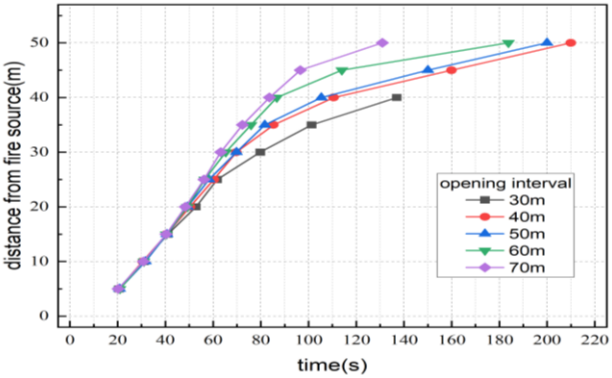

Fig. 5. Smoke spread distance under different opening intervals.

3.2 Effect of Opening Interval on Ceiling Temperature Distribution

Figure 6 illustrates the maximum temperature beneath the ceiling along the centerline of the tunnel for different opening intervals. It can be observed that the impact of the opening interval on the distribution of ceiling temperature between the fire source and the front side of the first ceiling opening is minimal. This is because the maximum ceiling temperature above the fire source is primarily influenced by the heat release rate of the fire source. The attenuation of the maximum ceiling temperature is primarily a result of heat transfer between the smoke and the ceiling and side walls. The change in the opening interval does not significantly affect this process. However, it is worth noting that a smaller opening interval leads to a closer proximity of the ceiling temperature drop point to the fire source.

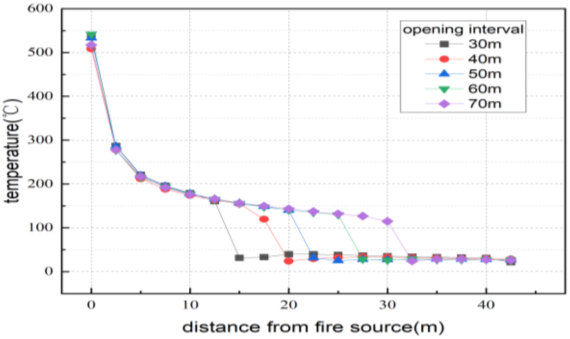

Fig. 6. Ceiling temperature distribution under different opening intervals.

3.3 Effect of opening interval on visibility

Figure 7 depicts the visibility slices along the centerline of the tunnel near the fire source for each opening interval. It can be observed that the opening interval has a limited impact on the visibility near the fire source. However, the opening interval significantly influences the visibility distribution behind the opening. A larger opening interval corresponds to higher overall visibility behind the opening. For instance, when the opening interval is set at 30 m, the smoke discharged from the first group of roof openings is restricted, leading to a considerable amount of smoke remaining behind the opening and lower visibility. Conversely, when the opening interval is 70 m, there is almost no smoke behind the opening, resulting in high visibility.

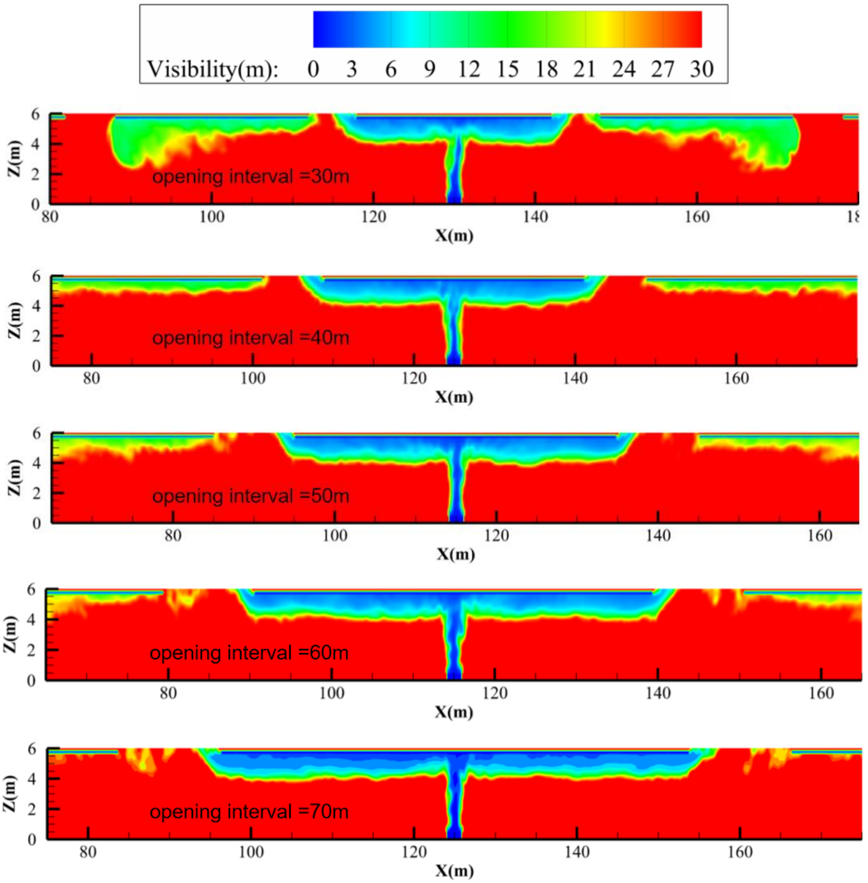

Fig. 7. Visibility distribution under different opening intervals.

4 Conclusion

A series of numerical simulations were conducted to investigate the influence of opening interval on the smoke exhaustion based on an underground fire lane of Chongqing Metro. Several conclusions can be addressed based on simulation results:

1. Reducing the opening interval can indeed enhance the control of smoke spread. Smaller opening intervals result in shorter total smoke spread distances and slower smoke front propagation.
2. The opening interval does not significantly affect the distribution of ceiling temperature between the fire source and the roof opening. However, decreasing the opening interval can reduce the extent of the high-temperature area on the ceiling.
3. The opening interval does not have a notable impact on the visibility distribution near the fire source. However, increasing the opening interval generally leads to higher overall visibility behind the roof opening.

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