Study on Parameters setting of Semi Transverse Smoke Exhaust in Subway Tunnel

Hong Hao¹, Guangyuan Zhang¹*
¹ School of Municipal and Environmental Engineering, Shenyang Jianzhu University, Shenyang, Liaoning, China
*Corresponding author’s e-mail: hj_hh@sjzu.edu.cn

Abstract: By using fire dynamics software with PyroSim, the fire smoke flow in subway tunnel with semi transverse smoke exhaust mode is numerically simulated, and a variety of combination modes of semi transverse smoke exhaust are simulated to observe the smoke flow in subway tunnel. The author sets up a variety of smoke exhaust schemes by changing the distance, area and volume of smoke exhaust. The smoke flow and temperature field under different conditions are compared to analyse the exhaust efficiency of each exhaust outlet and the total exhaust efficiency. It provides a reference for the setting of semi transverse smoke exhaust system in subway tunnel.

1. Introduction
Subway is an important mode of transportation. Tunnel smoke extraction methods are divided into natural and mechanical. There are two types of machinery: longitudinal and transverse. The longitudinal mode is relatively simple, there is no need for special air duct, but there will be passengers walking in the smoke. Horizontal smoke exhaust is divided into full level smoke exhaust and half level smoke exhaust. The former has high initial investment and maintenance costs, and the exhaust outlet needs automatic control, so it is not used basically. The semi transverse smoke exhaust system is equipped with a special flue at the top of the tunnel to discharge high temperature flue gas nearby and reduce the diffusion range of flue gas [1-5]. At present, there are few researches on semi transverse ventilation. How to set the parameters and how to arrange the exhaust outlet need to be studied systematically.

2. Establishment of subway tunnel model

2.1. Physical model
The elevation of Shenyang metro tunnel area is shown in Figure 1, 120m on one side, and the scale is 1:1. The tunnel is simplified as a cuboid with a width of 6m and a height of 4m. Figure 2 shows the whole picture of the model established by FDS software. According to the evaluation report of China's rail transit engineering, the peak value of fire source intensity caused by subway compartment fire is generally 6.8MW [6]. According to 《GB51298-2018》, the design fire scale of Metro is 7.5~10.5 MW [7]. The fire source is 8MW and the area is 0.6m×0.6m, the combustion product is polyurethane. Based on the tunnel model, a semi transverse smoke exhaust system is added. Assume that one of the exhaust valves is just above the fire source.
2.2. Boundary condition and the mesh settings of the model

The initial temperature is set at 20℃and the pressure is 101.325kpa. Both ends of the tunnel are set as open boundaries. The wall is a fixed temperature boundary condition. When the train is running, it will produce piston airflow along the direction of the train, which is called the piston action of the train [8]. If the train stops quickly in case of fire, it does not exist. FDS technical manual suggests that the ratio of flame characteristic length $D^*$ grid sized $dx$ should be controlled between 4 and 16. During combustion, the characteristic length $D^*$ of flame is calculated as follows:

$$D^* = \left( \frac{Q}{\rho_\infty T_\infty C_\infty \sqrt{g}} \right) \frac{z}{x}$$  \hspace{1cm} (1)

In the formula: $Q$—Power of fire source, kw; $\rho_\infty$—Air density, kg/m³; $C_\infty$—Specific heat capacity of air, kJ/(kg·K); $T_\infty$—Ambient temperature, K; $g$—Acceleration of gravity, m/s.

In order to determine the reasonable grid size, three grid sizes of 0.2m, 0.25m and 0.5m are used for simulation and comparison. A smoke vent is set up directly above the fire source, the smoke exhaust volume is 40 m³/s, the time is 360s, and the heat release rate is shown in Figure 3. The heat release rate is about 8000kw. When the grid size is 0.5m, the value of fire power is more divergent, while when the grid size is 0.2m and 0.25m, the value is relatively convergent. Therefore, in this simulation, the grid size is set as 0.25m×0.25m×0.25m, and the total number of grids is 215040.

3. Numerical simulation results and analysis

The code [9] requires that the evacuation time should not exceed 6 minutes after the fire. According to NFPA investigation, the volume fraction of CO in case of fire should not be higher than $2\times10^{-3}$, otherwise the personnel will show signs of poisoning [10]. So monitor the temperature and carbon monoxide concentration. The layout of measuring points is shown in Figure 4.
3.1. Influence of location and number of exhaust outlets on smoke flow distribution

The longitudinal distribution of the tunnel is shown in Figure 5, and the length of the smoke exhaust area is controlled within 100m. According to 《DG/TJ 08-2033-2017》, when the smoke outlet is set at the top of the tunnel, the distance should not be more than 60m. The smoke exhaust volume is set as 60 m³/s, the size of smoke outlet is set as 600mm×1200mm, the spacing is set as 10m, 20m, 30m, 40m and 50m, the number is 9, 5, 3, 3 and 3, and they are named as working conditions 1, 2, 3, 4 and 5.

![Figure 5. Longitudinal distribution of the tunnel](image)

It can be seen from Figure 6 that the flue gas control effect of condition 3 is the best. The temperature of condition 1 and 2 is slightly lower than that of condition 3, which indicates that shortening the distance can improve the effect. Condition 4 is the worst. Too many exhaust ports will reduce the wind speed and increase the local resistance. If the exhaust port is too small, the wind speed will be too high, and the smoke layer will be inhaled to reduce the effective exhaust volume. It can be seen from figure 7 that the CO concentration is less than $2\times10^{-3}$, so the system is feasible and effective.

![Fig 6. Temperature distribution at different distances](image)

![Fig 7. Case 4: CO concentration distribution](image)

3.2. Influence of exhaust volume on smoke flow distribution

The exhaust volume can be calculated according to the following formula:

$$C_s = 21 \left(1 - e^{-V_e \cdot t/V}\right)$$  \hspace{1cm} (2)

$$V = 20(A_o - A_V)$$  \hspace{1cm} (3)

$$C_s \leq 0.1$$  \hspace{1cm} (4)

In the formula: $C_s$—Allowable flue gas concentration m³/s; $V_e$—Exhaust volume of equipment, m³/min; $V$—Effective volume, m³; $t$—the end time of evacuation, min; $A_o$—effective area perpendicular to the line direction (deducting columns, stairs or escalators, etc.), m²; $A_V$—cross sectional area of train, m².

The calculated exhaust volume shall not be less than 83.3m³/min, which shall be converted into equivalent proportion. When the effective length is 120m, the minimum smoke discharge of one side track within the effective calculation length is 35.28m³/s; Other lengths are calculated by linear interpolation. Five working conditions of 40m³/s, 50m³/s, 60m³/s, 70m³/s and 80m³/s are studied, named as working conditions 5, 6, 7, 8 and 9. The size of smoke outlet is set as 600mm×1200mm, the number is 3, and the spacing is 30m. The temperature distribution of combustion for 100s simulated in Fig. 8, and the flue gas is asymmetrically distributed on both sides of the fire source. The smoke layer is stable and thin when the exhaust volume reaches 80 m³/s. The temperature field distribution in the tunnel simulated by FDS at 360s after the start of combustion is shown in Fig. 9.
Figure 10 shows the temperature distribution in the center profile after 360s of combustion, and hydraulic jump occurs in the area close to the fire source. The control effect of the system on the flue gas temperature increases with the increase of the exhaust volume, when the exhaust volume reaches 60 m³. The results show that the temperature above the fire source decreases obviously and the smoke control effect is greatly improved. According to GB51298-2018 [7], the wind speed in the metal smoke exhaust duct is less than 20 m/s, and in the non-metal smoke exhaust duct is less than 15 m/s, and the wind speed at the smoke exhaust outlet should not be greater than 7 m/s. Condition 6 is the most unfavorable condition. Figure 11 shows the CO concentration slice at the height of 1.5 m when the combustion time is 360 s under working condition 6. It can be seen that the CO concentration is less than 2×10⁻³ everywhere, so the system is feasible and effective.

3.3. Influence of exhaust port size on smoke flow distribution

In this group of simulation, the exhaust outlets are set as 600mm×600mm, 600mm×1200mm, 1200mm×1200mm, named as working conditions 10, 11 and 12, the exhaust volume is set as 60 m³/s, three exhaust outlets are set, and the spacing is 30 m. In Figure 12, when the shape of the air outlet is rectangular, the flue gas temperature decreases obviously, but when it is far away from the fire source, there is not much difference between rectangular and square. Square can reduce the diffusion of flue gas although it has poor control intensity. When far away from the fire source, there is no significant difference. Therefore, the rectangular exhaust valve is selected and the side length is not easy to be too large. The CO concentration in Figure 13 is less than 2×10⁻³, so the system is effective.
4. Conclusion

- The semi transverse smoke exhaust system can control the temperature of the smoke at 1.5m to a lower level, and the CO concentration meets the requirements, which is conducive to personnel evacuation and fire rescue.
- Under the setting conditions in this chapter, the best setting is when the distance between smoke outlets is 30m.
- With the increase of exhaust volume, the effect is obvious. On the premise of meeting the specification, the exhaust volume should be increased as much as possible.
- The size of the exhaust port has little effect on the efficiency, but the rectangular exhaust port is better than the square exhaust port.

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References

[1] Choi, J.S. (2005) Experimental Investigation on Smoke Propagation in a Transversely Ventilated Tunnel. J. Journal of Fire Sciences., 23(6): 469-483.
[2] Li, J.S.M., Chow, W.K. (2003) Numerical studies on performance evaluation of tunnel ventilation safety systems. J. Tunnelling and Underground Space Technology., 18(5): 435-452.
[3] Kurioka, H., Oka, Y., Satoh, H., Sugawa, O. (2003) Fire properties in near field of square fire source with longitudinal ventilation in tunnels. J. Fire Safety Journal., 38(4): 319-340.
[4] Ko, G.H. (2010) An experimental study on the effect of slope on the critical velocity in tunnel fires. J. Journal of Fire Sciences., 28(1): 27-47.
[5] Jiang, Y.Q., Huo, R., Hu, L.H., etc. (2010) Influence of transverse extraction rates on smoke stratification characteristics in channel fires. J. Engineering Mechanics., 27(7):250-256.
[6] Cui, G.X. (2004) Progress in large eddy simulation of turbulent flows. J. Acta Aerodynamica Sinica., 22(2):121-129.
[7] Ministry of Public Security of the People's Republic of China. (2018) Standard for fire protection design of metro.GB51298-2018. S. China Planning Press.
[8] Dong, S.Y. (2008) Piston Effect on the Subway Station and Its’ Utilization in the North of China. D. Tianjin University.
[9] Ministry of Housing and Urban-Rural Development of People’s Republic of China. (2013) Code design of metro. GB50157-2013. S. China Architecture & Building Press.
[10] Huang, Y.D., Li C., Kim N.C. (2012) A numerical analysis of the ventilation performance for different ventilation strategies in a subway tunnel. J. Journal of Hydrodynamics., 24(2): 193-201.