Numerical Simulation on Smoke Control for Extra-Long Tunnel Fires

Wenbo Liu, Junmei Li, and Yanfeng Li

Abstract Based on an actual project in Beijing, this article investigates the effect of smoke control strategies on smoke extraction efficiency under different fire source locations of the point smoke extraction system in extra-long tunnels using Airpak software. The results show that when a fire occurs in a tunnel, the smoke extraction efficiency of the tunnel smoke extraction system varies greatly depending on the location of the fire source and the adoption of different smoke extraction strategies. Due to the suction of the smoke exhaust shaft fan, the relative distance between the electric smoke exhaust valve and the entrance of the tunnel is close, which will cause the smoke exhaust valve within a certain range to be plug-holing, seriously affecting the smoke exhaust effect of the smoke exhaust system. Smoke exhaust valve beyond this range, although not occurring plug-holing the smoke exhaust efficiency is also relatively low, by changing the opening strategy of the smoke exhaust valve can effectively improve the smoke exhaust valve plug-holing, so as to improve the smoke exhaust efficiency.

Keywords Smoke Control · Extra-long · Fire · Simulation

1 Introduction

With the continuous improvement of China's transportation capacity and tunnel construction level, a large number of highway tunnels have been built nationwide, a significant portion of which are extra-long tunnels. According to the relevant specifications, the length of the tunnel is greater than 3,000 m that belongs to the extra-long tunnel. The structure of extra-long highway tunnels is relatively complex, long in depth, confined and narrow in space, once a fire occurs, the high temperature and smoke generated by the fire is difficult to discharge in time, which will not only affect the structural safety of the tunnel itself, but also pose a great threat to the escape and

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rescue of tunnel personnel. Therefore, it is crucial to vent the hot smoke from the tunnel in time when a fire occurs [1].

Scholars at home and abroad attach great importance to the safety of tunnel fires and have conducted a lot of research, including theoretical analysis, numerical simulation and experimental studies, which provide theoretical support for tunnel fire smoke control as well as safety protection.

Hu et al. [2] conducted an experimental study on the smoke temperature and stratification height distribution characteristics of highway tunnel fires and found that the smoke temperature decays exponentially with power below the tunnel vault and the smoke layer settles as the distance of smoke spread increases, posing a threat to personnel evacuation.

Du et al. [3] found in a study of the temperature distribution of the tunnel strong plume driven roof jet that the maximum temperature in the fire region without longitudinal ventilation in the tunnel is not much related to the heat release rate of the fire source, which is around 820 °C. However, the range of the high temperature region increases with the increase of the heat release rate and the decrease of the relative distance between the fire source and the roof.

Xu [4] analyzed and studied the smoke decay rate of fire in the exhaust vent of long tunnels and found that the smoke temperature below the top plate of the near-wall fire source is the highest and the value is higher than the same fire source located in the center position. J. Ji and R. Huo et al. [5] found that the smoke extraction efficiency of mechanical smoke extraction is influenced by the relative position of the fire source and the smoke vent, and the smoke flow condition in long tunnels is different from that of ordinary buildings, and the smoke vent should not be set in the thought spreading stage, and the distance from the fire source should not be greater than 1.33 times the width of the tunnel. In one end of the open channel for mechanical smoke evacuation, not the more smoke venting is started, the more evenly distributed the better the smoke evacuation effect, it is appropriate to start the smoke vent on the opposite side of the filler vent alone or simultaneously start the smoke vent on both sides of the fire source, while in the two ends of the open channel for mechanical smoke evacuation, it is appropriate to start the smoke vent on both sides of the fire source.

In the study of centralized smoke exhaust in extra-long highway tunnels, Zhang. [6] conducted a numerical simulation of the effect of the size of the smoke vent and the spacing of the smoke vent on the smoke exhaust effect of a centralized smoke exhaust system in a highway tunnel in Zhejiang, and found that the smoke exhaust effect of point smoke extraction is better, and the smoke can be controlled within an effective distance, the larger the area of the smoke vent the larger the effective smoking area, and the better the smoke exhaust effect; the spacing of the smoke vent has a relatively small effect on the smoke exhaust effect, and both 25 m and 50 m can meet the smoke exhaust requirements.

Although a lot of research has been conducted on focused smoke extraction, there are still many issues that require continuous in-depth research to ensure that smoke extraction systems can operate safely and effectively in actual projects, and that smoke is controlled in a safe range during fires, while supplementing and theoretically supporting existing codes.

2 Method

2.1 Physical Model

The physical model of the tunnel is shown in Fig. 1. and Fig. 2. The tunnel section is 9096 m long, 13 m wide, and 8.5 m high, with a smoke venting mezzanine height of 1.5 m. There are three smoke shafts at the top of the tunnel, with an effective smoke exhaust size of 5 × 6 m. The distance between shaft 1 and shaft 2 is 2567.159 m, and the distance between shafts 2 and 3 is 4769.134 m, which are asymmetrically distributed. The exhaust volume of the fan used in shaft 1 is 200 m^3/s and the wind pressure is 2700 pa, the exhaust volume of the fans in shaft 2 and shaft 3 is 180 m^3/s and the wind pressure is 2417 pa. The electric smoke exhaust valve on the smoke exhaust roof is 3 m long and 2 m wide, and the spacing between smoke exhaust valves is 60 m.

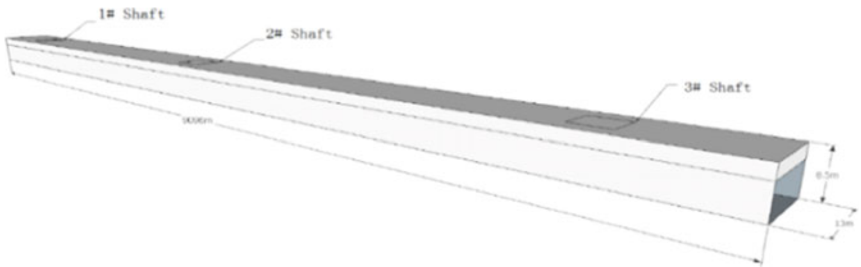


Fig. 1 Geometry of the tunnel model

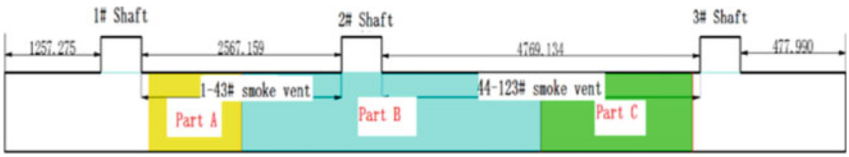


Fig. 2 Overview map of the actual tunnel project

2.2 Fire Scenarios

According to the survey of the type of vehicles passing through the tunnel, and with reference to domestic and international norms on the fire size of different types of vehicles inside the tunnel, and considering that the tunnel is closed to some large tankers, the fire power of the study is set at 50 MW.

2.3 Governing Equations

The flow of fluids is controlled by the laws of physical conservation, the basic control equations include, Continuity equation, Momentum equation, Energy equation and k-ε equation.[7] According to the conservation of mass in the micro-element per unit time, The continuity equation:

$$\frac{\partial \mathrm{u}}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

The rate of change of the momentum of a fluid in a micro-element with respect to time is equal to the sum of the various external forces acting on the micro-element. According to this law, the conservation of momentum equation is

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial\left(\rho u^2\right)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

The rate of increase of energy in the microelement is equal to the net heat flux into the microelement plus the work done on the microelement by the body force and the surface force. This law is actually the first law of thermodynamics. According to this law, the energy equation is derived as follows:

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} = \left(\frac{\lambda}{C_P}\right) + \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

where u and v are the velocity components of the fluid in the x and y directions, respectively, ρ is the fluid density, T is the fluid temperature, p is the pressure of the fluid, μ is the dynamic viscosity coefficient, λ is the thermal conductivity of the fluid and C_p is the constant pressure specific heat capacity.

k Turbulent kinetic energy transport equation:

$$\frac{\partial(\rho k u_x)}{\partial x} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right] + G_k + G_b + \rho\varepsilon, G_k = -\rho u'_x u'_y \frac{\partial u_y}{\partial u_x} \tag{4}$$

ε Turbulent kinetic energy dissipation rate transport equation:

$$\frac{\partial(\rho\varepsilon u_x)}{\partial x} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{u_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + G_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}, G_b = \beta_g\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial T}{\partial x} \tag{5}$$

where, k is the turbulent kinetic energy, μ_t is the turbulent viscosity, σ_k, σ_ε are the turbulent Prandtl numbers of k and ε, respectively. G_k is the turbulent kinetic energy generated by the mean velocity gradient. G_b is the turbulent kinetic energy generated by buoyancy. ε is the turbulent kinetic energy dissipation rate. C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are constants. β is the expansion coefficient.

2.4 Boundary Condition Setting

The wall is adiabatic condition, the entrance at both ends of the tunnel is set as a free boundary, and the smoke exhaust shaft is set with both exhaust air volume and wind pressure conditions, and the outdoor temperature is 20°C.

2.5 Grid Independence Test

When the software performs simulation calculations, the density of the mesh and the quality of the mesh will directly affect the calculation results. After several simulations of models with different grid sizes, the maximum temperature of the top plate at different locations from the fire source was counted as a reference value, and the results are shown in Fig. 3. The grid size is $1 \times 1 \times 1$ m and $0.7 \times 0.7 \times 0.7$ m calculation results basically match. However, because the tunnel model is too large, the grid size is set too small, which will lead to too many total grids increasing the unnecessary calculation time, so the model grid size is set to $1\times 1\times 1$ m and the number of grids is 2800000.

2.6 Working Conditions Setting

In the event of a fire, this study investigates the effect of different smoke evacuation strategies on the smoke evacuation efficiency of the tunnel by adjusting the location of the fire source in the tunnel, changing the opening status of fans in different shafts or changing the opening strategy of electric smoke exhaust valves. region A and region C have similarity, and only region A will be studied in the article, 8 working conditions are set in the simulation, as shown in Table 1. Conditions 1–4 simulate the fire source is located in region A, using shaft 1 with different smoke exhaust valve opening strategy; Conditions 5–8 simulate the fire source is located in region

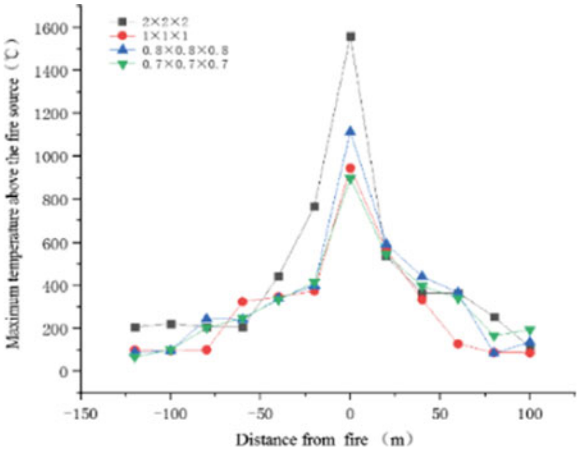


Fig. 3 Temperature distribution of top plate with different grid sizes

Table 1 Simulated working conditions setting

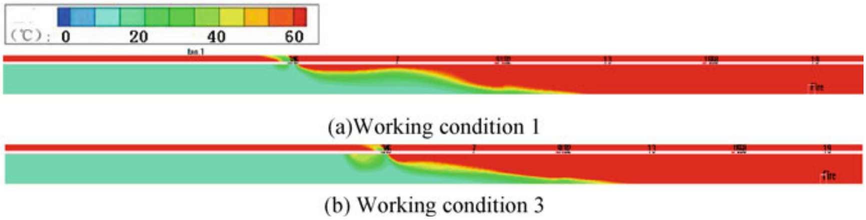
NO	Fire Location	Code of open smoke exhaust valve	Distance of fire source from left tunnel entrance	Smoke vent opening strategy
1	Region A	1–6	1451 m	3–3
2		2–7	1451 m	2–4
3		7–12	1811 m	3–3
4		8–13	1811 m	2–4
5	Region B	38–43	3647 m	3–3
6		37–42	3647 m	4–2
7		44–49	4021 m	3–3
8		45–50	4021 m	2–4

B using shaft 2 smoke exhaust. The 3-3, 2–4, and 4-2 in the working condition are the number of electric smoke exhaust valves opened on both sides of the fire source.

3 Results and Discussion

3.1 Fire Source Located in Region A

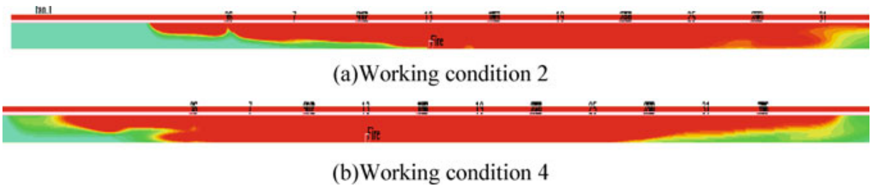
Smoke Exhaust Valve Opening Strategy for 3-3. In the event of a fire in this area, three smoke exhaust valves are opened upstream and downstream of the fire source for smoke exhaust, using smoke exhaust valves No. 1–6 for smoke exhaust, No. 1 smoke exhaust valve will plug-holing obviously, as the fire source position right, the use of 3–8, 7–12, 8–13 groups of smoke exhaust valve for smoke exhaust,



(a)Working condition 1

(b) Working condition 3

Fig. 4 Smoke spread under different fire source locations in region A



(a)Working condition 2

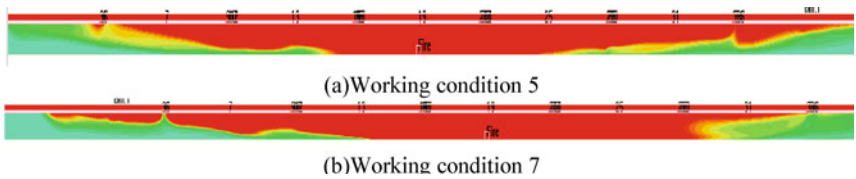
(b)Working condition 4

Fig. 5 Smoke spread diagram after changing the opening strategy in region A

the leftmost end of the smoke exhaust valve closer to the No. 1 shaft will also occur suction through the phenomenon, until the beginning of the 9th smoke exhaust valve, smoke exhaust valve suction through the phenomenon began to disappear. However, their efficiency will be relatively low, mainly due to the fact that this section is closer to the exit on the left side of the tunnel, and the axial fan in Shaft 1 has a relatively large smoke discharge, the simulation results are shown in Fig. 4.

Smoke Exhaust Valve Opening Strategy for 2–4. Compare the fire source upstream and downstream each open three smoke exhaust valves, the third smoke exhaust valve on the left side of the fire source will be closed, while in the right side of the fire source and then open a smoke exhaust valve, at this time the spread of smoke in the tunnel as shown in Fig. 5.

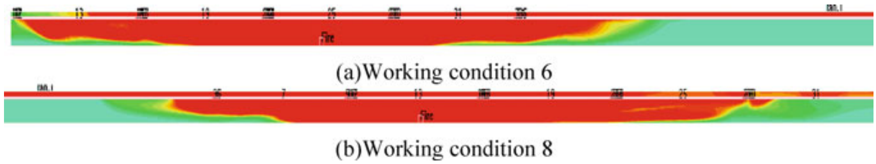
According to the simulation results, with the smoke exhaust strategy of 2–4, the overall distance of smoke spread is significantly reduced compared with Case 1 and Case 3 under the opening strategy of 3–3, while the smoke exhaust valve's suction penetration phenomenon is also improved and the smoke exhaust efficiency is increased.



(a)Working condition 5

(b)Working condition 7

Fig. 6 Smoke spread under different fire source locations in region B



(a)Working condition 6

(b)Working condition 8

Fig. 7 Smoke spread diagram after changing the opening strategy in region B

3.2 Fire Source Located in Region B

The fire source is in area B, using the fire source on each side of the opening of three smoke exhaust valves, shaft 2 on both sides of the nearest smoke exhaust valve will not occur suction through the phenomenon, but in a critical suction through the state, at this time the smoke exhaust efficiency of the smoke exhaust valve will be relatively low. The simulation results are shown in Fig. 6.

Smoke Exhaust Valve Opening Strategy for 3-3.

Smoke Exhaust Valve Opening Strategy for 2–4 (4-2). The smoke exhaust valve close to the shaft, although no suction through the phenomenon, but close to the critical state, the smoke exhaust efficiency is very low, the smoke spreads a long distance, is not conducive to the evacuation of people in the tunnel, when the same smoke exhaust strategy as above, that is, close the smoke exhaust valve close to the shaft, while opening one on the other side of the fire source, so that the smoke exhaust efficiency of the smoke exhaust valve will improve, while the smoke spreads a distance will be controlled in a limited This way, the smoke exhaust valve will be more efficient and the smoke spread will be controlled within a limited distance. The results of the smoke spread simulation are shown in Fig. 7.

4 Conclusion

In this study, the efficiency of smoke exhaust valves under different smoke exhaust strategies during focused smoke exhaust in tunnels was investigated by means of Airpak numerical simulations, with the following conclusions.

(1) When the fire occurs in area A or C, within a distance of the fire source close to the shaft, the smoke exhaust valve is relatively close to the smoke exhaust shaft, which will cause some of the smoke exhaust valves to be absorbed through the phenomenon or in a critical state of absorption through, Severe reduction in smoke extraction efficiency and excessive distance of smoke spread in the tunnel, it is not conducive to the evacuation of people in the tunnel.
(2) Due to the long depth of the extra-long tunnel, when in area B, the tunnel longitudinal wind speed is reduced, at this moment the smoke exhaust valve closer to the shaft suction through the phenomenon is not obvious, but the smoke exhaust efficiency will still be affected, the same change in smoke exhaust strategy to improve the smoke exhaust efficiency.
(3) In the actual project, the design of the key smoke exhaust system should fully consider the impact of the location of different fire sources and the relative distance between the smoke exhaust valve and the shaft on the smoke exhaust efficiency, and can take different smoke exhaust strategies according to different flame zones, or take intelligent control of the smoke exhaust system to flexibly adjust the smoke exhaust strategy.

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