Understanding the indicators in the quantitative method of evaluating the smoke exhaust performance provides a theoretical basis for the optimization of the smoke extraction system under the lateral centralized mode in tunnel fires. The criterion was proposed for plug-holing, and the theoretical models of smoke exhaust efficiency were established to distinguish whether the plug-holing occurs or not. The relationship between efficiency, effectiveness, and efficacy was analyzed from the perspective of smoke and heat exhaust. Meanwhile, this evaluation method was applied to the optimization of exhaust volume in a practical engineering through FDS numerical simulation. The results show that $R_i$ is a vital basis for reflecting the movement form of smoke and the exhaust effect. The critical value of $R_i$ is 1.09 when plug-holing occurs in a standard three-lane immersed tunnel, resulting in a significant reduction in the efficiency of smoke exhaust. The greater the exhaust volume of the exhaust fan, the greater the $R_i$ value, the higher the total smoke and heat exhaust efficiency, and the better the exhaust effectiveness of smoke inlets without plug-holing. Under longitudinal ventilation, the optimal exhaust volume is 180 m$^3$/s at 20 MW and 360 m$^3$/s at 50 MW in the application case.

**Keywords** Tunnel fires · Evaluation method · Smoke exhaust performance · Lateral centralized mode · Exhaust volume · Plug-holing

**Abstract**

This study investigated the indicators in the quantitative method of evaluating the smoke exhaust performance, which provided a theoretical basis for the optimization of the smoke extraction system under the lateral centralized mode in tunnel fires. The criterion was proposed for plug-holing, and the theoretical models of smoke exhaust efficiency were established to distinguish whether the plug-holing occurs or not. The relationship between efficiency, effectiveness, and efficacy was analyzed from the perspective of smoke and heat exhaust. Meanwhile, this evaluation method was applied to the optimization of exhaust volume in a practical engineering through FDS numerical simulation. The results show that $R_i$ is a vital basis for reflecting the movement form of smoke and the exhaust effect. The critical value of $R_i$ is 1.09 when plug-holing occurs in a standard three-lane immersed tunnel, resulting in a significant reduction in the efficiency of smoke exhaust. The greater the exhaust volume of the exhaust fan, the greater the $R_i$ value, the higher the total smoke and heat exhaust efficiency, and the better the exhaust effectiveness of smoke inlets without plug-holing. Under longitudinal ventilation, the optimal exhaust volume is 180 m$^3$/s at 20 MW and 360 m$^3$/s at 50 MW in the application case.

**Introduction**

In recent years, to shorten the distance of traffic and improve the efficiency of transportation, the number of highway tunnels continues to increase in China. Therefore, the proportion of long and large highway tunnels accounted for an increasingly high and rapid growth trend. While the risk of tunnel fire is also increasing. Accident cases show that if the high-temperature and toxic smoke generated by the fire were not controlled effectively and discharged in time, it would cause serious consequences and hazards (Xu et al. 2018).

As highway tunnels continue to cross towards offshore water areas, immersed tube tunnels begin to be widely applied to cross rivers, seas, and lakes. However, it is difficult for people to escape and rescue as they are built underwater. Therefore, high expectations are placed on the design of the smoke extraction system. From this, the lateral centralized smoke exhaust mode is usually adopted to reduce the high-temperature and toxic smoke. It operates by remotely controlling the opening of multiple groups of smoke inlets near the fire source, jet fans in the tunnel, and the exhaust fan in the smoke duct, so as to control the smoke within a certain range and discharge it (Xu et al. 2019a). In this way, it not only prevents the smoke from moving upstream, but also shortens the spreading distance and residence time downstream, providing a good environment for the evacuation and rescue of personnel. The principle is that the opening of the exhaust fan will cause the difference in pressure between the tunnel and the smoke duct, and the smoke will be sucked and continuously discharged from the smoke inlets (Xu et al. 2022). Since multiple groups of...
smoke inlets are arranged longitudinally along the tunnel and have been distributed to different locations, and the suction effect on the smoke inlets at different locations is also different, it is difficult to accurately measure the smoke exhaust performance. And several factors must be considered, including the arrangement of the smoke inlets and the exhaust volume of the exhaust fan. As a result, the application of quantitative indicators to evaluate smoke exhaust performance is crucial for the efficient discharge of high-temperature toxic smoke.

At present, scholars have established and applied quantitative evaluation indicators such as smoke exhaust efficiency and heat exhaust efficiency, which have obtained certain results in optimizing the smoke exhaust performance in tunnel fires (Guo et al. 2021; Takeuchi et al. 2018; Tanaka et al. 2021; Yi et al. 2015). In addition, Ji et al. (2010) and Li et al. (2013) found that the phenomenon of plug-holing would occur when the exhaust volume was too large.

In the aspect of optimization research of smoke exhaust performance under lateral centralized smoke exhaust mode in tunnel fires, Xu et al. (2019b) analyzed the effects of smoke exhaust rate and smoke inlet size on heat removal by numerical simulation and theoretical analysis. Liu et al. (2021) used the smoke exhaust efficiency to explore the effect of different supplementary smoke ducts opening forms on the smoke exhaust of an extra-wide immersed tube tunnel. Li et al. (2021a) also adopted this indicator to judge the smoke exhaust effect of the lateral centralized smoke exhaust mode when using the activated vertical smoke screens, and pointed out that the construction of smoke control zones could optimize the smoke exhaust performance. Xu et al. (2022) comprehensively considered the smoke exhaust efficiency and heat exhaust efficiency of the smoke inlets and the smoke extraction system, analyzed the influence of the exhaust volume on them, and obtained the optimal exhaust volume. Jiang et al. (2018) and Zhong et al. (2021) found that the smoke exhaust efficiency was low in the lateral centralized smoke exhaust mode when the exhaust volume was too large, within the situation the plug-holing occurred.

From this, there were deviations in the definitions of the evaluation indicators of smoke exhaust performance. The indicators such as smoke exhaust efficiency and heat exhaust efficiency were mostly used separately, and the quantitative relationship between smoke exhaust efficiency and plug-holing had not been established. Meanwhile, it was rarely considered that the effect of improving the smoke exhaust performance would be not obvious when larger exhaust volume existed, resulting in the waste of exhaust fan efficacy. Since the smoke extraction system discharges the smoke, it also discharges the heat, it is necessary to comprehensively evaluate the smoke exhaust performance of the smoke extraction system according to several indicators such as plug-holing, smoke exhaust efficiency and heat exhaust efficiency. In addition, since multiple groups of smoke inlets are opened and the exhaust volume has a great influence on the exhaust performance, it is necessary to comprehensively compare the smoke inlets and the smoke extraction system to provide a basis for the optimization of exhaust volume.

On this basis, this study established the theoretical models and illustrated the relationships of each evaluation indicator, where the plug-holing under the lateral centralized smoke exhaust mode was taken into account to obtain a complete quantitative evaluation method. Furthermore, the method was applied to the optimization of exhaust volume by numerical simulation based on a practical engineering, so that the influence of exhaust volume on various evaluation indicators was analyzed. It is hoped that this work can guide the design of the smoke extraction system, realizing energy savings while maintaining safety and reliability.

### The indicators of the smoke exhaust performance evaluation method

#### The criterion for plug-holing

After a tunnel fire occurs, the high-temperature smoke will be generated by the combustion of the fire source, forming an upward-moving fire plume. And the smoke will hit the tunnel ceiling due to the obstruction after floating up, and then will spread freely around the radial direction until it meets the restriction of the walls. As a result, it will gradually change from radial movement to horizontal flow, and it will eventually spread longitudinally along the tunnel.

In the lateral centralized smoke exhaust mode, it is necessary to turn on the jet fans in the tunnel to provide longitudinal ventilation after the fire occurs, so as to ensure the safe evacuation and escape of personnel from upstream of the fire source. The wind speed is relatively large, which made the longitudinal smoke movement in the tunnel wind-driven rather than buoyancy-driven (Zhong et al. 2013). Meanwhile, the exhaust fan in the smoke duct needs to be turned on to provide lateral suction, so that the smoke in the tunnel is continuously discharged from the smoke inlets through the smoke duct. Based on that, the smoke at the smoke inlets is affected by the vertical thermal buoyancy, the gravity, the reaction force, the longitudinal driving force of ventilation, and the lateral suction force. It is also subjected to the shear force generated by the relative movement of the
smoke and the air, as well as the friction resistance with the tunnel walls, as shown in Fig. 1.

The shear force and friction resistance are both small, which are negligible compared with the suction force and driving force. And the vertical movement distance of the smoke is also small, it can be approximately regarded as an equilibrium state. Therefore, the lateral suction force and longitudinal driving force play a dominant role in the lateral centralized smoke exhaust process. It differs from the vertical exhaust mode, which is mainly affected by vertical thermal buoyancy and longitudinal inertia force (Jiang et al. 2021).

When the suction force does not exceed the driving force, the disturbance effect on the smoke is weak. Consequently, very little of the smoke flows from the tunnel into the smoke duct through the smoke inlets, while most of the smoke continues to move downstream of the smoke inlets. But when the suction force exceeds the driving force, a large amount of smoke is discharged from the smoke inlets. And if the smoke was not enough to be quickly replenished to the smoke inlets, the fresh air under the smoke layer would be directly inhaled. At this point, the disturbance effect of the smoke layer is significantly enhanced, and the smoke discharged from the smoke inlets contains a mass of fresh air. That is the plug-holing occurs, resulting in a significant decrease in the smoke exhaust performance can be evaluated according to whether or not the plug-holing occurs.

$R_i$ has been used to recognize the movement pattern of smoke (Ji et al. 2012), and it can be applied to determine whether the plug-holing occurs at the smoke inlets. The $R_i$ in the lateral centralized mode can be defined as the ratio of the suction effect’s motive force to the ventilation’s driving force at the upstream of the smoke inlets, which is expressed as Eq. (1).

$$R_i = \frac{\rho_{se,i} \cdot v_{se,i}^2 \cdot A_{se,i}}{\rho_{si} \cdot v_{si}^2 \cdot A_{si}} = \frac{\rho_{se,i} \cdot v_{se,i}^2 \cdot h_{si,i} \cdot w_{si,i}}{\rho_{si} \cdot v_{si}^2 \cdot w_{si,i}} \quad (1)$$

where $\rho_{se,i}$ and $\rho_{si}$ denote the densities of smoke in smoke inlets $i$ and upstream of smoke inlets $i$, $v_{se,i}$ and $v_{si}$ denote the flow velocities of smoke in smoke inlets $i$ and upstream of smoke inlets $i$, $A_{se,i}$ and $A_{si}$ denote the areas of the smoke in smoke inlets $i$ and upstream of smoke inlets $i$, $V_{se,i}$ denotes the exhaust volume in the smoke inlets $i$, $h_{si,i}$ denotes the thickness of the smoke layer in the upstream of smoke inlets $i$, $w_{si,i}$ denotes the width of the smoke layer in the upstream of smoke inlets $i$.

The $R_i$ value when the plug-holing occurs is the critical value. And when the $R_i$ exceeds the critical value, the smoke exhaust performance decreases.

The smoke exhaust efficiency and heat exhaust efficiency

The smoke extraction system not only discharges the smoke, but also discharges the heat. Therefore, the typical hazard factors in highly toxic and high-temperature smoke, should be chosen to evaluate the exhaust performance. To put it another way, the efficiency of smoke and heat exhaust should be considered from the standpoint of smoke inlets and the smoke extraction system (Xu et al. 2022).

When no plug-holing occurs, the smoke exhaust efficiency of smoke inlets in each group was investigated in the previous study, and it can be taken as Eq. (2) (Xu et al. 2022).

$$n_{se,i} = \frac{1 - a_{x,i}(1 + m_{s,i}/m_{si})}{b_{x,i} - a_{x,i}} = \frac{1 - a_{x,i}C_{s,i}}{b_{x,i} - a_{x,i}} - \frac{a_{x,i}C_{s,i} - 1}{b_{x,i} - a_{x,i}} \sum_{i=1}^{n} n_{se,i} \quad (2)$$

with

$$a_{x,i} = C_{s,i} / C_{s,i} \quad (3)$$

$$b_{x,i} = C_{se,i} / C_{s,i} \quad (4)$$

$$C_{s,i} = C_{s,i} / C_{s,i} \quad (5)$$
where \( m_{s,i} \) denotes the mass flow rate of the entrained air at smoke inlets \( i \), \( m_{s,i} \) denotes the mass flow rate of smoke upstream of smoke inlets \( i \), \( C_{s,i} \) and \( C_{s',i} \) denote the concentrations of toxic smoke upstream and downstream of smoke inlets \( i \), \( C_{se,i} \) denotes the concentration of toxic smoke discharged from smoke inlets \( i \), \( C_{s,i}' \) and \( C_{s,i}' \) denote the concentrations of toxic smoke upstream and downstream of smoke inlets \( i \) when the smoke inlets are closed.

When the plug-holing occurs, the mixing effect of high-temperature smoke and cold air is strengthened. Consequently, part of the air is mixed into the smoke layer and discharged from the smoke inlets, while the other part continues to move downstream. At this time, Eq. (6) can be obtained.

\[
\eta_{se,i} = \frac{m_{s,i} - m_{se,i}}{m_{s,i}}
\]  

(6)

Therefore, the smoke exhaust efficiency when the plug-holing occurs is obtained as Eq. (7).

\[
\eta_{se,i} = \frac{1 - a_{s,i}(1 + \frac{b_{s,i} m_{se,i}}{m_{s,i}})}{b_{s,i} - a_{s,i}}
\]  

(7)

In Eq. (7), \( m_{s,i}/m_{s,i} \) reflects the degree of air entrainment when the plug-holing occurs. The smaller the value is, the less air is entrained due to the plug-holing, and the higher the smoke exhaust efficiency is.

When no plug-holing occurs, the total smoke exhaust efficiency of the smoke extraction system can be taken as Eq. (8) (Xu et al. 2022).

\[
\eta_{se} = \frac{m_{s}}{m_{s}} = \frac{\sum_{i=1}^{n} \eta_{se,i}'}{C_{s}'/C_{s}} - C_{s} + \sum_{i=1}^{n} \frac{C_{se,i}'}{C_{s}'} \eta_{se,i}'
\]  

(8)

where \( m_{s} \) denotes the total mass flow rate of the smoke exhaust, \( m_{s} \) and \( C_{s} \) denote the mass flow rate of smoke and concentration of toxic smoke generated by combustion, \( C_{s}' \) and \( C_{s}' \) denote the concentrations of toxic smoke after discharged when the smoke inlets are opened and after longitudinal spreading when the smoke inlets are closed.

When the plug-holing occurs, it can be considered that \( m_{s} \) is the sum of air mass flow rate of the entrained due to the plug-holing, and the total smoke exhaust efficiency is expressed as Eq. (9).

\[
\eta_{se} = \frac{m_{se} - m_{a}}{m_{s}} = 1 - \frac{C_{s}}{C_{s}'} - \sum_{i=1}^{n} \frac{C_{se,i}'}{C_{s}'} \eta_{se,i}'
\]  

(9)

The heat exhaust efficiency of smoke inlets in each group can be expressed as Eq. (10) (Xu et al. 2022).

\[
\eta_{he,i} = \frac{\rho_{se,i} v_{se,i} A_{se,i} \Delta T_{se,i}}{\rho_{s,i} v_{s,i} A_{s,i} \Delta T_{s,i}}
\]  

(10)

where \( \Delta T_{se,i} \) and \( \Delta T_{s,i} \) denote the temperature rises in smoke inlets \( i \) and upstream of smoke inlets \( i \).

It is worth noting that the calculation of heat exhaust efficiency is not affected by plug-holing. And the total heat exhaust efficiency of the smoke extraction system can be expressed as Eq. (11) (Xu et al. 2022).

\[
\eta_{he} = \sum_{i=1}^{n} c_{p} \rho_{se,i} v_{se,i} A_{se,i} \Delta T_{se,i}/Q
\]  

(11)

where \( c_{p} \) denotes the specific heat at constant pressure, \( Q \) denotes the heat release rate (HRR).

The smoke exhaust effectiveness and heat exhaust effectiveness

According to the definition, \( Ri \) represents the movement pattern of smoke, and it is directly related to the ability of the smoke inlets to discharge smoke (Ji et al. 2012). Therefore, the \( Ri \) can also be used to judge the effect of smoke exhaust and heat exhaust.

Since

\[
m_{se,i} = \rho_{se,i} v_{se,i} A_{se,i}
\]  

(12)

\[
m_{s,i} = \rho_{s,i} v_{s,i} h_{s,i} w_{s,i}
\]  

(13)

Hence, the relationship between smoke exhaust effectiveness and smoke exhaust efficiency can be obtained when no plug-holing occurs, as shown in Eq. (14).

\[
R_{i} = \frac{m_{se,i} v_{se,i}}{m_{s,i} v_{s,i}} = \frac{\eta_{se,i}'}{v_{s,i}}
\]  

(14)

Equation (15) can be derived when plug-holing occurs.

\[
R_{i} = \frac{m_{se,i} v_{se,i}}{m_{s,i} v_{s,i}} = \left( \eta_{se,i} + \frac{m_{s,i}}{m_{s,i}} \right) \frac{v_{se,i}}{v_{s,i}}
\]  

(15)

Similarly, the relationship between heat exhaust effectiveness and heat exhaust efficiency can be obtained as Eq. (16).

\[
R_{i} = \frac{m_{se,i} v_{se,i}}{m_{s,i} v_{s,i}} = \frac{\eta_{he,i} v_{s,i} \Delta T_{s,i}}{v_{s,i} \Delta T_{se,i}}
\]  

(16)

In this way, the quantitative relationship between the efficiency, effectiveness and \( Ri \) is established to evaluate the smoke exhaust performance. When the phenomenon of
plug-holing does not occur, the higher the efficiency, the better the effectiveness.

The smoke exhaust efficacy and heat exhaust efficacy

As the exhaust volume of the exhaust fan increases, the smoke and heat exhaust efficiency will increase accordingly. However, when the exhaust volume reaches a certain value, the efficiency will not be greatly improved. Not only will the phenomenon of plug-holing occur, but also energy will be wasted in the case.

In this paper, the smoke exhaust efficacy is defined as the ratio of the increase in smoke exhaust efficiency to the increase in exhaust volume. And the heat exhaust efficacy is defined as the ratio of the increase in heat exhaust efficiency to the increase in exhaust volume. The formulas for calculating the smoke exhaust efficacy and heat exhaust efficacy of smoke inlets in each group are shown in Eq. (17) and Eq. (18).

\[
k_{se,i} = \frac{\Delta \eta_{se,i}}{\Delta V_{ef}}
\]

(17)

\[
k_{he,i} = \frac{\Delta \eta_{he,i}}{\Delta V_{ef}}
\]

(18)

where \(\Delta \eta_{se,i}\) and \(\Delta \eta_{he,i}\) denote the increase in \(\eta_{se,i}\) and \(\eta_{he,i}\), \(\Delta V_{ef}\) denotes the increase in \(V_{ef}\).

In the same way, the smoke exhaust efficacy and heat exhaust efficacy of the smoke extraction system can be obtained as Eq. (19) and Eq. (20).

\[
k_{se} = \frac{\Delta \eta_{se}}{\Delta V_{ef}}
\]

(19)

\[
k_{he} = \frac{\Delta \eta_{he}}{\Delta V_{ef}}
\]

(20)

where \(\Delta \eta_{se}\) and \(\Delta \eta_{he}\) denote the increase in \(\eta_{se}\) and \(\eta_{he}\).

When the smoke exhaust efficacy and heat exhaust efficacy reach a large value, it indicates that increasing the exhaust volume at this stage can greatly improve the smoke and heat exhaust, and the smoke exhaust performance is better.

The application of the evaluation method in exhaust volume optimization

Numerical modeling

The physical model

Based on the smoke exhaust performance evaluation method, an application case was provided for the optimization of exhaust volume in this study. The physical model of the immersed tube tunnel was established in the FDS. And the dimensions and locations of smoke inlets and smoke duct referred to the geometric dimensions of a standard three-lane immersed tunnel (Xu et al. 2018), as shown in Fig. 2. The slope of the tunnel was ignored.

The tunnel entrance and exit boundary were configured to simulate longitudinal ventilation and the natural open state, respectively. And the end of the smoke duct was configured to simulate the exhaust fan. The tunnel length was 300 m, which was long enough to simulate the smoke spreading in this condition. The material of the tunnel wall was concrete with a thickness of 0.7 m. The ambient temperature was set to 20 °C.

Fig. 2 The physical model of tunnel in simulation
The fire source and mesh grid size

The ramp-up time of the fire source was set as the default, and the length of the fire source was 8.0 m and the width is 2.5 m, which could represent a fire of a light duty truck (HRR is 20 MW) or a draft truck (HRR is 50 MW) in the tunnel. It was located in the longitudinal center of two groups of smoke inlets (one group was upstream of the fire source and the other group was downstream of the fire source). Its specific location was \( X = 48.75 \) m. The yield of CO and soot was set as 0.006 and 0.008 respectively.

In order to obtain accurate simulation results, the reasonable grid cell size should be obtained. The method is to calculate the fire characteristic diameter, which is expressed as Eq. (21). A range of grid cell size can be obtained according to the recommendation (Mcgrattan et al. 2013).

\[
D^* = \left( \frac{Q}{\rho_a c_p T_a \sqrt{g}} \right)^{2/5} \tag{21}
\]

The results of the calculation demonstrate that the grid cell size of 20 MW is within 0.20–0.80 m, and the grid cell size of 50 MW is within 0.30–1.20 m. Therefore, six sizes within this range are selected to verify the sensitivity of the grid in the fire stabilization stage. As shown in Fig. 3, when the grid size is less than or equal to 0.5 m, the accuracy is not improved much. Given the effect of grid cell size on simulation calculation time and the need for model matching, it is 0.1 m \( \times \) 0.1 m \( \times \) 0.1 m in the smoke inlets and 0.5 m \( \times \) 0.3 m \( \times \) 0.3 m in other areas, allowing for greater accuracy. The total number of grids was 838,440.

The simulation cases

It can be calculated by the formula of the minimum exhaust volume that the minimum requirement is 97.2 m\(^3\)/s for 20 MW and 198.4 m\(^3\)/s for 50 MW (Li et al. 2021a). Through numerical simulation, it was found that the smoke can be controlled within 300 m when the longitudinal ventilation was 2.5 m/s under 20 MW and 3 m/s under 50 MW. Additionally, the length of the back-layering was extremely small, which was conducive to the evacuation and escape of personnel, as well as the fighting and rescue work of firefighters from upstream. Based on this, several cases were set to investigate the influence of exhaust volume on various evaluation indicators of smoke exhaust performance, as shown in Table 1. And the time when the fire reached the stabilization stage was selected to obtain the simulation results, which was 250–300 s.

Results and discussion

Influence of exhaust volume on plug-holing

Whether the phenomenon of plug-holing will occur can be determined according to the height of smoke layer interface, and it can be obtained by FDS based on the smoke temperature integral ratio method (Jiang et al. 2018). If the height of smoke layer interface was lower than the height of the smoke inlets, a large amount of fresh air would be discharged during the smoke inlets, then the plug-holing occurs.

Table 1 Simulation cases

| Cases | HRR   | Longitudinal ventilation | Exhaust volume (\( V_{ef} \)) |
|-------|-------|--------------------------|-------------------------------|
| A1–A6 | 20 MW | 2.5 m/s                  | 120, 140, 160, 180, 200, 220 m\(^3\)/s |
| B1–B5 | 50 MW | 3.0 m/s                  | 240, 280, 320, 360, 400 m\(^3\)/s |

Table 2 The height of smoke layer interface when the plug-holing occurs

| HRR    | Smoke inlets | Exhaust volume (\( V_{ef} \)) | The height of smoke layer interface |
|--------|--------------|-------------------------------|-----------------------------------|
| 20 MW  | Smoke inlets | 180 m\(^3\)/s                | 5.01 m                            |
|        |              | 200 m\(^3\)/s                | 5.06 m                            |
|        |              | 220 m\(^3\)/s                | 5.21 m                            |
| 50 MW  | Smoke inlets | 400 m\(^3\)/s                | 5.08 m                            |
|        | Smoke inlets | 240 m\(^3\)/s                | 5.05 m                            |
|        |              | 280 m\(^3\)/s                | 5.12 m                            |
|        |              | 320 m\(^3\)/s                | 5.17 m                            |
|        |              | 360 m\(^3\)/s                | 5.31 m                            |
|        |              | 400 m\(^3\)/s                | 5.43 m                            |
As shown in Table 2, the plug-holing occurs at the smoke inlets 4 when the $V_{ef}$ is greater than 180 m$^3$/s under 20 MW, and it occurs at the smoke inlets 3 when the $V_{ef}$ is greater than 400 m$^3$/s under 50 MW. In particular, it occurs at the smoke inlets 4 with different exhaust volumes under 50 MW. The larger the exhaust volume, the higher the interface height of the smoke layer at the smoke inlets 3 and 4, and the greater the possibility of plug-holing. It reveals that with the exhaust volume increases and the distance from the exhaust fan decreases, the difference in pressure increases. Therefore, the ratio of the suction effect’s motive force to the ventilation’s driving force increases. However, when the smoke spreads to the smoke inlets 3 and 4, its content decreases significantly, and the height of smoke layer interface increases. As a result, the smoke cannot be quickly replenished to the smoke inlets, and a large amount of fresh air is entrained in the exhausted smoke, making it impossible to be discharged effectively.

Figure 4 shows the $R_i$ value calculated by Eq. (1). It can be observed that the $R_i$ at the smoke inlets where the plug-holing occurs is greater than 1.09, so the critical value of $R_i$ to determine whether the plug-holing occurs is 1.09. At this time, the motive force generated by the suction effect is equivalent to the driving force generated by ventilation. As can be seen from Fig. 4, the larger the $V_{ef}$, the larger the $R_i$, and the bigger the possibility of plug-holing. In other words, the value of $R_i$ increases with the increase of the $V_{ef}$, which attributes to an extremely rapid increase in the ratio of the suction effect’s motive force to the ventilation’s driving force.

Figure 4 shows the $R_i$ value calculated by Eq. (1). It can be observed that the $R_i$ at the smoke inlets where the plug-holing occurs is greater than 1.09, so the critical value of $R_i$ to determine whether the plug-holing occurs is 1.09. At this time, the motive force generated by the suction effect is equivalent to the driving force generated by ventilation. As can be seen from Fig. 4, the larger the $V_{ef}$, the larger the $R_i$, and the bigger the possibility of plug-holing. In other words, the value of $R_i$ increases with the increase of the $V_{ef}$, which attributes to an extremely rapid increase in the ratio of the suction effect’s motive force to the ventilation’s driving force.

**Influence of exhaust volume on smoke and heat exhaust efficiency**

Since CO in the toxic smoke is a typical hazardous factor in tunnel fires, the CO concentration is chosen as the concentration of toxic smoke to evaluate the exhaust performance in this paper.

Figure 5 shows the $\eta_{se,i}$ value calculated by Eq. (2) and Eq. (7). For different HRRs and different group of smoke inlets, the $\eta_{se,i}$ all shows a trend of “first increase and then decrease” with the increase of $V_{ef}$. Therefore, it is not conducive to the discharge of smoke when the exhaust volume is too small or too large. In other words, $\eta_{se,i}$ is low in the case of smaller exhaust volume and larger exhaust volume, which is related to the ratio of the suction effect’s motive force to the ventilation’s driving force.

It can be noticed that except for the smoke inlets 4, $\eta_{se,i}$ reach the maximum value when $V_{ef}$ = 180 m$^3$/s under 20 MW. Compared with 120 m$^3$/s, it is increased by 42.9–75.4%. At this time, $\eta_{se,4}$ is only 32.8% of that when $V_{ef}$ = 160 m$^3$/s. It can be found that the phenomenon of plug-holing greatly reduces the smoke exhaust efficiency. When the HRR is 50 MW, the $\eta_{se,i}$ is extremely low due to the phenomenon of plug-holing at the smoke inlets 4. In general, the other groups of smoke inlets are higher when $V_{ef}$ = 360 m$^3$/s under 50 MW. Compared with 240 m$^3$/s, it is increased by 47.3–144.0%.

Figure 6 shows the $\eta_{he,i}$ value calculated by Eq. (10). As can be seen, the closer the smoke inlets to the exhaust fan, the higher the $\eta_{he,i}$. This is because smoke inlets 1 is located further away from the exhaust fan, the suction
force is much smaller than the driving force, resulting in a small amount of heat is discharged. And the heat discharged from the smoke inlets increases as the ratio of the suction effect’s motive force to the ventilation’s driving force increases.

The \( \eta_{he,i} \) shows a trend of “first increase significantly and then decrease slightly” with the increase of \( V_{ef} \). It can be noticed that except for \( V_{ef} = 220 \text{ m}^3/\text{s} \), the \( \eta_{he,i} \) increases gradually with the increase of \( V_{ef} \). Therefore, the \( \eta_{he,i} \) is the largest when \( V_{ef} = 200 \text{ m}^3/\text{s} \). But the improvement of the \( \eta_{he,i} \) is slightly smaller, which is 7.9–13.1% higher than that of 180 m\(^3\)/s. And the \( \eta_{he,i} \) at 180 m\(^3\)/s is 10.2–16.2% higher than that of 160 m\(^3\)/s.

It can be seen that except for the smoke inlets 4, the \( \eta_{he,i} \) increases gradually with the increase of the \( V_{ef}' \) under 50 MW. The disturbance effect of the smoke layer at the
smoke inlets 4 is extremely strong when $V_{ef} = 400 \text{ m}^3/\text{s}$, so the $\eta_{he,i}$ fluctuates greatly, which is significantly lower than that of $360 \text{ m}^3/\text{s}$. On the whole, when $V_{ef} = 360 \text{ m}^3/\text{s}$, the $\eta_{he,i}$ is higher, which is 1.23–2.16 times that of $240 \text{ m}^3/\text{s}$.

Figure 7 shows the $\eta_{se}$ and $\eta_{he}$ calculated by Eq. (8), Eq. (9), and Eq. (11). As can be seen, with the increase of $V_{ef}$, $\eta_{se}$ and $\eta_{he}$ are both improved under different HRRs. It shows that the larger the exhaust volume, the better the effect of exhausting the high-temperature and toxic smoke in the tunnel.

In addition, with the increase of $V_{ef}$, the increase rate of the $\eta_{he}$ is higher than that of $\eta_{se}$. It indicates that the increase of $V_{ef}$ has a better effect on improving $\eta_{he}$ than $\eta_{se}$. It is because the temperature is mainly affected by convection and radiation, and the concentration of toxic smoke is mainly affected by diffusion (Hu et al. 2010; Li et al. 2021b). The different control mechanisms of the two lead to a rapid decrease in temperature, and a slow decrease in the concentration of toxic smoke during the exhaust process. Therefore, the heat attenuation in the tunnel is faster than that of toxic smoke when the exhaust volume is increased.

The $\eta_{se}$ is equivalent to $\eta_{he}$ when $V_{ef} = 180 \text{ m}^3/\text{s}$ under 20 MW, which are 1.09 times and 1.57 times that of 120 m$^3$/s. The $\eta_{se}$ is equivalent to the $\eta_{he}$ when $V_{ef} = 360 \text{ m}^3/\text{s}$ under 50 MW, which are 1.10 times and 1.40 times that of 240 m$^3$/s. It is found that the further increase of $V_{ef}$ has little effect on improving the $\eta_{se}$ and $\eta_{he}$. Not only will the plug-holing occur, but the exhaust fan’s efficacy will be lost. That is, the energy is being wasted, and the operating cost is rising.

Influence of exhaust volume on smoke and heat exhaust effectiveness

The $Ri_i$ representing the exhaust effectiveness can be recalculated according to Eq. (14)–Eq. (16), and the relationship between exhaust effectiveness and exhaust efficiency can be obtained. It can be observed from Fig. 8 (a) that when no plug-holing occurs, as the distance from the exhaust fan decreases, the difference in pressure increases. That is, the suction force increases, leading to the increase of $v_{se,i}$ and $Ri_i$. In descending order, the values under the same exhaust volume are as follows: $Ri_4$, $Ri_3$, $Ri_2$, and $Ri_1$. According to the results in the “Influence of exhaust volume on smoke and heat exhaust efficiency” section, it can be accountable for the $\eta_{se,i}$ that exhibits a zigzag trend of “first increase, then decrease, and then increase” with the increase of the $Ri_i$.

When the $V_{ef}$ is small, the $\eta_{se,i}$ at the same smoke inlets increases with the increase of the $V_{ef}$, and the smoke flow velocity shows the same trend. Therefore, the suction effect is enhanced with the increase of the $V_{ef}$, and the $Ri_i$ increases gradually. When the $V_{ef}$ is increased to a certain value, the plug-holing will occur at the smoke inlets 4. At this time, the lateral suction force on the smoke is equivalent to the longitudinal ventilation driving force. Continuing to increase the $V_{ef}$, the $\eta_{se,i}$ will decrease instead. And the larger the $V_{ef}$, the lower the $\eta_{se,i}$. What is more, the degree of air entrainment at the smoke inlets will increase, and the smoke flow rate at the smoke inlets will increase significantly. Therefore, the $Ri_i$ will increase significantly. It can be seen that when the plug-holing occurs, the $\eta_{se,i}$ shows a trend of “first increase and then decrease” with the increase of $Ri_i$.  

Fig. 7 $\eta_{se}$ and $\eta_{he}$ under different exhaust volumes
As shown in Fig. 8 (b), except for \( V_{ef} = 400 \text{ m}^3/\text{s} \), the changing trend under 50 MW is consistent with the above. When \( V_{ef} = 400 \text{ m}^3/\text{s} \), with the increase of the \( R_{ii} \) value, the \( \eta_{se,i} \) shows a zigzag trend of “first increase, then decrease, and then increase”. This variation is different from the above because the plug-holing occurs at the smoke inlets 3 under 400 \( \text{m}^3/\text{s} \), resulting in lower \( \eta_{se,i} \), which is even lower than that at the smoke inlets 4.

It can be seen from Fig. 9 that the \( R_{ii} \) value increases with the increase of the \( \eta_{he,i} \) at the same \( V_{ef} \) under 20 MW and 50 MW. This is because the closer the smoke inlets to the exhaust fan, the higher the \( \eta_{he,i} \), the greater the \( v_{se,i} \), and the smaller the difference in temperature ratio. According to Eq. (16), it can be seen that the \( R_{ii} \) is larger in this case.

It can also be seen from Fig. 9 that when the plug-holing occurs, with the increase of the \( \eta_{he,i} \), the growth rate
of the $R_i$ is significantly greater than that of no plug-holing occurs. This is because the plug-holing occurs at the smoke inlets, which are located closer to the exhaust fan. When the $\eta_{he,i}$ increases, the smoke flow velocity at the smoke inlets increases, and the $R_i$ increases faster, which is consistent with the above analysis. When no plug-holing occurs, the $R_i$ shows an increasing trend with the increase of $V_{ef}$, because the $\eta_{he,i}$ increases with the increase of $V_{ef}$.

Overall, when the $R_i$ is lower than the critical value of the plug-holing, the higher the exhaust efficiency, the better the exhaust effectiveness. Therefore, it should be ensured that the plug-holing with least groups of smoke inlets, and the exhaust volume when the $\eta_{se,i}$ and $\eta_{he,i}$ are higher should be selected as the optimal exhaust volume. It can be seen that when $V_{ef}$ is 180 m$^3$/s under 20 MW and $V_{ef}$ is 360 m$^3$/s under the 50 MW, $\eta_{se,i}$ and $\eta_{he,i}$ are all at a high value despite the plug-holing that occurs at the smoke inlets.

**Influence of exhaust volume on smoke and heat exhaust efficacy**

According to Eq. (17)–Eq. (20), the variation of the exhaust efficacy in each group of smoke inlets and the smoke extraction system can be obtained. As shown in Fig. 10, when the $V_{ef}$ under 20 MW is increased from 160 to 200 m$^3$/s, the exhaust efficiency is higher, and the $k_{he,i}$ and $k_{he}$ all show a trend of “first increase and then decrease”. And the $k_{se,i}$ shows a decreasing trend, while the $k_{se}$ does not change much. It is found that increasing the exhaust volume at this stage has little effect on improving the exhaust efficacy of the system, and is not conducive to the improvement of the exhaust performance of smoke inlets. It indicates the $\eta_{he,i}$ has an optimal value. As can be seen, when $V_{ef}$ is 180 m$^3$/s under 20 MW, the $k_{se,i}$ and $k_{he,i}$ are better, and the $\eta_{se,i}$ and $\eta_{he,i}$ can be improved without causing excessive energy waste. Therefore, the optimal exhaust volume is 180 m$^3$/s, which is 1.85 times the minimum exhaust volume.

When the $V_{ef}$ is increased from 320 to 400 m$^3$/s under 50 MW, the $k_{se,i}$ and $k_{he,i}$ show the same trend as that of 20 MW. With the increase of the $V_{ef}$, the $k_{se}$ is slightly improved, and the $k_{he}$ is slightly decreased. It can be found that the optimal exhaust volume is 360 m$^3$/s under 50 MW, which is 1.81 times the minimum exhaust volume. At this point, the smoke and heat exhaust efficacy can be promoted, and the excessive waste of energy will be perfectly avoided.

**Conclusions**

In this study, an evaluation method for smoke exhaust performance was established from the determination of the plug-holing, the smoke and heat exhaust efficiency, the smoke and heat exhaust effectiveness, and the smoke and heat exhaust efficacy. The relationship between the force of smoke, exhaust efficiency, exhaust effectiveness, and exhaust efficacy was analyzed and derived. An application case of a practical engineering was also provided to calculate the exhaust volume when the lateral centralized smoke exhaust mode with the best smoke exhaust performance. This research can help with smoke control, extraction system design, and emergency rescue in tunnel fires. The major findings are as follows:

![Fig. 10](image-url)
(1) The critical value of $Ri$ when the plug-holing occurs at the smoke inlet is 1.09 in the standard three-lane immersed tunnel. At this time, the suction force and the driving force have the same effect on the smoke.

(2) When no plug-holing occurs, the smoke exhaust efficiency and heat exhaust efficiency at the smoke inlets increase as the exhaust volume increases. When plug-holing occurs, the heat exhaust efficiency does not change significantly as the exhaust volume increases, while the smoke exhaust efficiency is greatly reduced. However, the total exhaust efficiencies of the system are improved, and the total heat exhaust efficiency outperforms the total smoke exhaust efficiency.

(3) The greater the exhaust volume, the higher the $Ri$ value, and the greater the possibility of plug-holing occurring in the smoke inlets closer to the exhaust fan. While the exhaust effectiveness of the smoke inlets improves when no plug-holing occurs.

(4) When each group of smoke inlets has a high exhaust efficiency, increasing the exhaust volume does not improve the exhaust efficacy. However, there is an optimal value for the heat exhaust efficacy.

(5) Taking into account all evaluation indicators, it is concluded that the optimal exhaust volume is 180 m$^3$/s under 20 MW and 360 m$^3$/s under 50 MW in the standard three-lane immersed tunnel. And the optimal exhaust volume is 1.81–1.85 times the minimum exhaust volume.

Author contribution Daqiang Zhu: Writing—original draft, Writing—review & editing, Formal analysis, Supervision; Pai Xu: Resources, Project administration, Funding acquisition, Methodology, Supervision; Rongjun Xing: Software, Visualization, Validation; Yufei Guo: Investigation, Simulation; Yixian Liu: Writing—editing, Visualization; Shuping Jiang: Validation, Methodology, Supervision; Linjie Li: Conceptualization, Methodology, Supervision.

Funding This research is funded by the National Natural Science Foundation of China (No. 52008068), the General Fund of Chongqing Natural Science Foundation (No. cstc2019jcyj-msxm0060), the State Key Laboratory of Mountain Bridge and Tunnel Engineering Fund Project (No. SKLB19–013), and Research and Innovation Program for Graduate Students in Chongqing (No. CYS19243).

Declarations

Competing interests The authors declare no competing interests.

References

Guo QH, Li YZ, Ingason H, Yan ZG, Zhu HH (2021) Theoretical and numerical study on mass flow rates of smoke exhausted from short vertical shafts in naturally ventilated urban road tunnel fires. Tunn Undergr Space Technol 111:103782. https://doi.org/10.1016/j.tust.2020.103782

Hu LH, Tang F, Yang D, Liu S, Huo R (2010) Longitudinal distributions of CO concentration and difference with temperature field in a tunnel fire smoke flow. Int J Heat Mass Transf 53:2844–2855. https://doi.org/10.1016/j.ijheatmasstransfer.2010.02.013

Ji J, Gao ZH, Fan CG, Zhong W, Sun JH (2012) A study of the effect of plug-holing and boundary layer separation on natural ventilation with vertical shaft in urban road tunnel fires. Int J Heat Mass Transf 55:6032–6041. https://doi.org/10.1016/j.ijheatmasstransfer.2012.06.014

Jiang XP, Bu QX, Xie ZY (2021) Influence of the concentrated smoke exhaust rate on the side of the tunnel on the smoke layer plug-holing. J Saf Environ 28:14–21 (in Chinese). https://doi.org/10.13578/cnki.jsen1671-1556.2021.02.002

Jiang XP, Liao XJ, Chen S, Wang J, Zhang SG (2018) An experimental study on plug-holing in tunnel fire with central smoke extraction. Appl Therm Eng 138:840–848. https://doi.org/10.1016/j.applthermaleng.2018.04.052

Ji J, Li KY, Zhong W, Huo R (2010) Experimental investigation on influence of smoke venting velocity and vent height on mechanical smoke exhaust efficiency. J Hazard Mater 177:209–215. https://doi.org/10.1016/j.jhazmat.2009.12.019

Li LJ, Gao ZH, Ji J, Han JY, Sun JH (2013) Research on the phenomenon of plug-holing under mechanical smoke exhaust in tunnel fire. Procedia Engineering 62:1112–1120. https://doi.org/10.1016/j.proeng.2013.08.168

Li LJ, Qiu QZ, Zhang XF, Xu P, Liu JL, Li YL, Fan CG (2021a) Assessment of different ventilation strategies on ventilation performance in immersed tunnels. Environ Sci Pollut Res 28:31838–31849. https://doi.org/10.1007/s11356-021-12818-9

Li LJ, Zhu DQ, Gao ZH, Xu P, Zhang WC (2021b) A study on longitudinal distribution of temperature rise and carbon monoxide concentration in tunnel fires with one opening portal. Case Studies in Thermal Engineering 28:101535. https://doi.org/10.1016/j.csite.2021.101535

Liu SL, Wang L, Yu MG, Jiang YD (2021) Optimization of smoke exhaust efficiency under a lateral central exhaust ventilation mode in an extra-wide immersed tunnel. Journal of Zhejiang University-Science A 22:396–406. https://doi.org/10.1631/jzus.A2000336

Megrattan KB, Mcdermott RJ, Weinschenk CG, Forney GP (2013) Fire dynamics simulator, user’s guide. Nist Special Publication Takeuchi S, Tanaka F, Yoshida K, Moinuddin, & K.A.M. (2018) Effects of scale ratio and aspect ratio in predicting the longitudinal smoke-temperature distribution during a fire in a road tunnel with vertical shafts. Tunn Undergr Space Technol 80:78–91. https://doi.org/10.1016/j.tust.2018.05.020

Tanaka F, Yoshida K, Ueda K, Ji J (2021) A simple model for predicting the smoke spread length during a fire in a shallow urban road tunnel with roof openings under natural ventilation. Fire Saf J 120:103106. https://doi.org/10.1016/j.firesaf.2020.103106

Xu P, Jiang SP, Xing RJ, Tan QJ (2018) Full-scale immersed tunnel fire experimental research on smoke flow patterns. Tunn Undergr Space Technol 81:494–505. https://doi.org/10.1016/j.tust.2018.08.009

Xu P, Xing RJ, Jiang SP, Li LJ (2019a) Theoretical prediction model and full-scale experimental study of central smoke extraction with a uniform smoke rate in a tunnel fire. Tunn Undergr Space Technol 86:63–74. https://doi.org/10.1016/j.tust.2019.01.014

Xu P, Zhu DQ, Xing RJ, Wen CY, Jiang SP, Li LJ (2022) Study on smoke exhaust performance in tunnel fires based on heat and smoke exhaust efficiency under the lateral centralized mode. Case Studies in Thermal Engineering 34:102002. https://doi.org/10.1016/j.csite.2022.102002
characteristics under lateral smoke exhaust in tunnel fires. Fire Mater 43:857–867. https://doi.org/10.1002/fam.2746

Yi L, Wei R, Peng JZ, Ni TX, Xu ZS, Wu DX (2015) Experimental study on heat exhaust coefficient of transversal smoke extraction system in tunnel under fire. Tunn Undergr Space Technol 49:268–278. https://doi.org/10.1016/j.tust.2015.05.002

Zhang SG, He K, Yao YZ, Peng M, Yang H, Wang JH, Cheng XD (2018) Investigation on the critical shaft height of plug-holing in the natural ventilated tunnel fire. Int J Therm Sci 132:517–533. https://doi.org/10.1016/j.ijthermalsci.2018.06.018

Zhong W, Fan CG, Ji J, Yang JP (2013) Influence of longitudinal wind on natural ventilation with vertical shaft in a road tunnel fire. Int J Heat Mass Tran 57(2):671–678. https://doi.org/10.1016/j.ijheatmasstransfer.2012.10.063

Zhong W, Sun CP, Bian HT, Gao ZH, Zhao J (2021) The plug-holing of lateral mechanical exhaust in subway station: phenomena, analysis, and numerical verification. Tunn Undergr Space Technol 112:103914. https://doi.org/10.1016/j.tust.2021.103914

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.