# Study on influence of breathing zone combined with underfloor makeup air supplement on smoke exhaust of road tunnel fire

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**Abstract.** In the era of rapid economic development, tunnel construction projects are increasing year by year in China, continuously expanding the urban network In the era of rapid economic development, tunnel construction projects are increasing year by year in China, continuously expanding the urban network radiation area, and accelerating the progress of the national modernization project. The subsequent tunnel traffic fire accidents are also increasing When a tunnel fire occurs, how to effectively supply makeup air to prevent the fire smoke from spreading to the evacuation passage of the When a tunnel fire occurs, how to effectively supply makeup air to prevent the fire smoke from spreading to the evacuation passage of the tunnel and exhaust the smoke as soon as possible has become a key concern in the field of tunnel disaster prevention. The layout of the smoke exhaust outlets under the mode of breathing zone combined with underfloor makeup air supplement was mainly used to study the problem of smoke exhaust in tunnel fires. The results show that under the same smoke exhaust flow rate, with the increase in the area of the results show that under the same smoke exhaust flow rate, with the increase in the area of the smoke outlet, the smoke exhaust efficiency of each exhaust outlet increases, and the total efficiency also increases. The width of the exhaust outlet has a significant effect on the smoke exhaust efficiency. However, the length of the exhaust vent has little effect on the efficiency of smoke exhaust. Under the mode of breathing zone combined with underfloor makeup air supplement, arranging smoke outlet with a size of 2 m × 1.5 m every 10 m has a better smoke extraction effect, and the total smoke exhaust efficiency can reach 75.77%. Fire safety of road tunnels has always been the focus of social concern. The makeup air supplement and smoke exhaust mode proposed in this study is expected the makeup air supplement and smoke exhaust mode proposed in this study is expected to provide a theoretical basis for the design of tunnel smoke prevention and exhaust systems.

**Keywords:** Tunnel fire, Numerical calculation, Breathing zone + Lower air supply, Smoke exhaust layout, Smoke exhaust efficiency

## 1 Introduction

When a tunnel fire occurs, in order to prevent the fire smoke from spreading into the tunnel evacuation passage, the correct air supply and smoke exhaust mode should be selected to ensure the safe operation of the tunnel.

In view of the characteristics of tunnel fires, scholars at home and abroad have carried out some researches. J.X. Huo et al. [1] conducted theoretical research and analysis on the required number of jet fans and air volume based on the relevant calculation parameters of the Guizhou YuZun expressway tunnel project and the relevant specifications for highway ventilation. R. Gao [2] first proposed a personalized makeup air system for tunnel fire escape using horizontal stall smoke drape walls and air supply vents to form a combination of breathing zone air supply and downdraft air supply, and the CO concentration in the escape route created by the makeup air flow is almost zero, providing a new perspective in the field of tunnel fire safety.

Y.C. Su [3] proposed a static plenum supplementary air exhaust mode in which the side breathing area supplementary air and the lower supplementary air of the smoke baffle were combined with the mechanical top exhaust, and the wind speed at the side air outlet was 0.7 m/s, and the downward ventilation was obtained. When the wind speed of the tuyere is 0.3 m/s, the smoke barrier effect in the escape passage can be guaranteed. Some scholars [4-6] studied the influence of the escape route space environment on the supplementary air in both directions, mostly focusing on the study of rescue strategies for the whole process of fire with certain influencing factors. In summary, the makeup air system combined with smoke exhaust system can control the smoke concentration in the escape tunnel.

Therefore, this study focuses on the breathing zone makeup air and lower makeup air combined with mechanical smoke exhaust mode of makeup air exhaust, to determine the effective control of smoke spread of the arrangement of the smoke vent form,and to compare the smoke exhaust efficiency.

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## 2 Numerical simulation

### 2.1 Physical model

This study will use the method of numerical simulation to study a highway tunnel. The tunnel [7] is 3300 m long, and the side walls, vault and ground are all made of concrete. The height is 5 m, and the flue is arc-shaped, located at the top of the roadway, as shown in Figure 1.

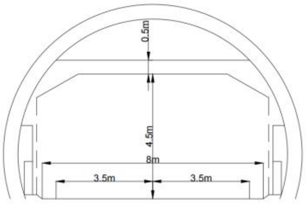


**Fig. 1.** Tunnel cross-section

### 2.2 Theoretical equations

When using FDS software to simulate, large eddy simulation (LES) is used to simulate. There are five basic equations for solving large eddy simulation in FDS, and each expression is as follows:

(1) Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \ (1)$$

$\rho$—Density, kg/m³ ;

$u$—Velocity vector, m/s;

(2) State equation

$$P_0 = \rho T R \sum Y_i / M_i \ \ (2)$$

$P_0$—Pressure, pa;

R—Gas constant, $J/(mol{\cdot}K)$;

$Y_i$—The mass fraction of the i-th component;

$M_i$ —The unit volume generation rate of the i-th component, $kg/(m^3{\cdot}s)$.

(3) Energy conservation equation

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \boldsymbol{u}) = \frac{Dp}{Dt} + Q - \nabla \cdot q + \varphi \ (3)$$

$h$—The enthalpy of the components, $kJ/kg$;

$Q$—Heat release rate of fuel, $kW/m^3$;

$q$—Radiant heat, $kW/m^2$;

$\varphi$—Fuel dissipation rate, $kW/m^3$.

(4) Momentum conservation equation

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}^2) + \nabla \cdot p = \rho f + \nabla \cdot \tau \ (4)$$

$p$—Internal pressure, pa;

$f$—External pressure, N;

$\tau$—Fuel viscosity, pa·s.

(5) Component conservation equation

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho Y_i \boldsymbol{u}) = \nabla \cdot p D_i \cdot \nabla \cdot Y_i + m_i \ (5)$$

$D_i$ —The diffusion coefficient of the i-th component, m²/s.

The formula for calculating the efficiency of the exhaust system is as follows:

$$\eta = \frac{M_e}{M_p} \times 100\% = \sum \eta_i = \frac{\sum M_{ei}}{M_p} \times 100\% \ (6)$$

η—Total fume extraction efficiency of fume extraction system；

$M_e$—The amount of flue gas discharged from all flue vents, kg/s;

$M_{ei}$—The amount of flue gas discharged from each exhaust port, kg/s;

$M_p$—Flue gas generation, kg/s.

### 2.3 Combustion model

Referring to the specifications of various countries to take the value of tunnel fire scale [8], the tunnel fire combustion is defined as unsteady combustion, and the value is 20 MW. The $t^2$ function is commonly used in FDS. The fire growth coefficient is taken as 0.1878 KW/s²The functional relationship is as follows.

$$Q = \alpha t^2 \ (7)$$

Q—Fire power, W.

α—Combustion growth factor.

t—Burning time, s.

### 2.4 Mesh independence verification

In order to determine a reasonable grid size, before the simulation, four working conditions were combined, and the feasibility of the four working conditions was judged by monitoring the temperature change of the measuring point 10 m downstream of the fire, as shown in Table 1.

**Table 1** grid division working condition table

| Work conditions | Near fire source size | Remote fire source size | Number of grids |
|---|---|---|---|
| A | 0.3×0.3×0.3 | 0.3×0.3×0.3 | 444180 |
| B | 0.15×0.15×0.15 | 0.3×0.3×0.3 | 696640 |
| C | 0.25×0.25×0.25 | 0.5×0.5×0.5 | 130560 |
| D | 0.2×0.2×0.2 | 0.4×0.4×0.4 | 21840 |

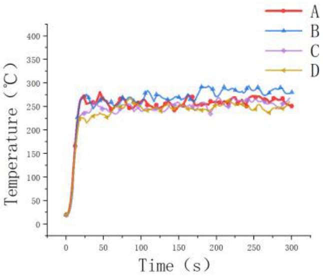


**Fig. 2.** Schematic diagram of grid division

It can be seen from Figure 2 that the numerical simulation calculation results of working conditions A, C and D are close to the real situation, and the reliability is high. Considering the requirements of computer performance and accuracy, select working condition C.

### 2.5 Model validation

The fire smoke temperature along the tunnel depth direction and the CO concentration along the tunnel depth direction were compared with the experimental data of Yu [9] and Y.H. Zhong[10]. It is found that the predicted values calculated by numerical simulation are in good agreement with the experimental data, as shown in Figure 3-4.

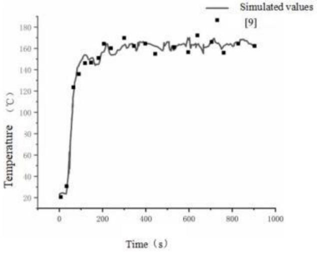


**Fig. 3.** Validation of model predicted temperature values against experimental data

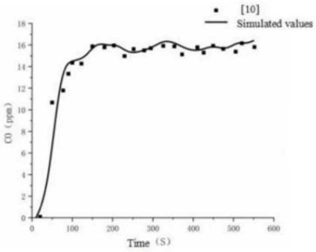


**Fig. 4.** Validation of model predicted CO concentration values against experimental data

## 3 Research content

### 3.1 Working condition setting

As shown in Figure 5-6, smoke exhaust method is mechanical smoke exhaust, set 2 m long and 1.5 m wide smoke exhaust air outlet, the center of the air outlet is set at y=0 m, z=5 m, and arranged one at 10 m interval along the length of the tunnel. The makeup air method is mechanical makeup air , with a slit-type makeup air opening in the breathing area, 200 m in length and 0.4 m in height, with the center of the opening set at y=-4 m, on the tunnel sidewall at z=1.75 m; a slit-type makeup air opening is set at ground level, 200 m in length and 0.4 m in width, with the center of the opening set at y=-3.7 m, at z=0 m ground level. Table 2 shows the details of the working conditions.

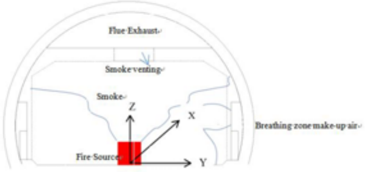


**Fig. 5.** Cross-sectional diagram of makeup air and smoke exhaust system

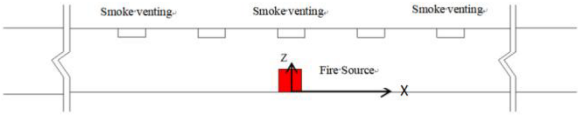


**Fig. 6.** Schematic diagram of the longitudinal section of the makeup air and smoke exhaust system

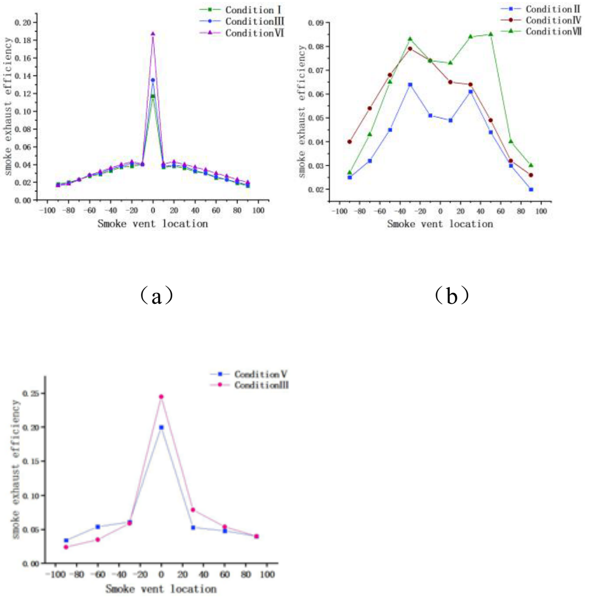
**Table 2.** Working condition setting

| Work conditions | Smoke vent size | Number of smoke exhaust ports | Smoke vent location (m) | Smoke exhaust air speed (m/s) |
|---|---|---|---|---|
| I | 1m×1m | 19 | 10 | 5.263 |
| II | 1m×1m | 10 | 20 | 10 |
| III | 2m×1m | 19 | 10 | 2.63 |
| IV | 2m×1m | 10 | 20 | 5 |
| V | 2m×1m | 7 | 30 | 7.143 |
| VI | 2m×1.5m | 19 | 10 | 1.754 |
| VII | 2m×1.5m | 10 | 20 | 3.33 |
| VIII | 2m×1.5m | 7 | 30 | 4.762 |

## 4 Analysis of results

### 4.1 Analysis of smoke exhaust efficiency

As shown in Figure 7, under the condition of a certain amount of smoke exhaust, as the area of the exhaust port increases, the exhaust efficiency of each exhaust port increases, and the total efficiency also increases.

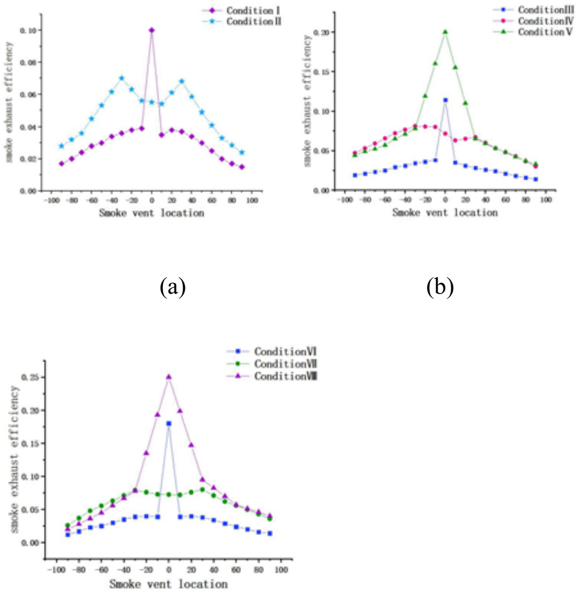


（a） （b）

（c）

**Fig. 7.** (a) Comparison of smoke exhaust efficiency of working condition I, III and VI (b) Comparison of smoke exhaust efficiency of working condition II, IV and VII (c) Comparison of smoke exhaust efficiency of working condition V and VIII

As shown in Figure 8, in the upstream and downstream areas of the fire source, the smoke exhaust efficiency is significantly better than that of the 1 ㎡ working condition when the smoke vent area is expanded to 2 ㎡ and 3 ㎡, but the smoke vent efficiency is similar at 2 ㎡ and 3 ㎡, indicating that the width of the smoke vent has a significant impact on the smoke exhaust efficiency.



(a) (b)

(c)

**Fig. 8.** (a) Comparison of smoke exhaust efficiency of working condition I and II (b) Comparison of smoke exhaust efficiency of working condition III, IV and V (c) Comparison of smoke exhaust efficiency of working condition VI, VII and VIII

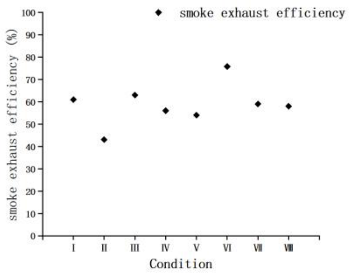


**Fig. 9.** Total smoke exhaust efficiency for working conditions

As shown in Figure 9, the fume extraction efficiency of the eight working conditions fluctuated from 43.04% to 75.77%.

## 5 Conclusion

The following conclusions can be drawn by comparing the smoke exhaust efficiency of working condition group I ~ working condition group VIII. When the area of the exhaust port is 1 m×1 m, the minimum value of the exhaust efficiency is 43.04%, and when the area of the exhaust port is 2 m×1.5 m, the maximum value of the exhaust efficiency is 75.77%. Under the condition of a certain amount of smoke exhaust, the smoke exhaust efficiency of each exhaust port is proportional to the area of the exhaust port. The exhaust port plays a major role in the exhaust system, greatly improving the exhaust efficiency of the system. the width of the exhaust port has a significant impact on the exhaust efficiency, and the length of the exhaust port has little effect on the exhaust efficiency. the study found that the working conditions VI has the highest smoke extraction efficiency, which can effectively gather smoke, and the total smoke extraction efficiency can be increased to 75.77%.

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