

# Study on the Spread Law of Smoke in Tunnel Fires under the Synergistic Effect of Longitudinal Ventilation and Scattered Exhaust Outlets

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## Abstract

Taking the Sutong Second Urban Area Expressway Tunnel as the background, this study aims to investigate the law of smoke spread in tunnel fires under the synergistic effect of longitudinal ventilation and scattered exhaust outlets. The numerical simulation method is adopted to analyze the longitudinal distribution of early-stage temperature, CO concentration and visibility during tunnel fires under different working conditions, so as to obtain the optimal smoke control strategy. When the number of scattered exhaust outlets is fixed, the higher the exhaust volume of a single scattered exhaust outlet is, the more effectively the smoke spread can be controlled. When the exhaust volume of a single scattered exhaust outlet is  $10 \text{ m}^3/\text{s}$ ,  $20 \text{ m}^3/\text{s}$  and  $30 \text{ m}^3/\text{s}$  respectively, there will be a great impact on the smoke exhaust effect, resulting in the inability to control the smoke and causing the smoke to enter the second smoke exhaust section, which poses a serious threat to the evacuation and rescue of people. When the exhaust volume is increased to  $40 \text{ m}^3/\text{s}$ , after the smoke passes through the scattered exhaust outlets, it does not spread to the next smoke exhaust section, and the smoke is effectively controlled, which is conducive to the evacuation and rescue of people and will not pose a serious threat to the evacuation and rescue of people. Therefore, under specific conditions, the synergistic effect of longitudinal ventilation and scattered exhaust outlets can well control the spread of smoke.

## Keywords

Tunnel Fire; Scattered Exhaust Outlets; Numerical Simulation; Temperature; Visibility; CO Concentration.

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## 1. Introduction

At present, there are 27,297 highway tunnels in China, with a total length of approximately 30.2318 million meters. Among them, there are 2,050 extra-long tunnels with a length exceeding 3,000 meters, with a total length of about 9.2407 million meters, and 7,552 long-distance tunnels with a length ranging from 1,000 meters to 3,000 meters, with a total length of approximately 13.2138 million meters<sup>[1]</sup>. Against this backdrop, while highway tunnels bring people traffic convenience, tunnel fires are one of the most common types of tunnel accidents. Once a fire breaks out in a tunnel, it will cause casualties and huge economic losses. Therefore, the research on the smoke control scheme for tunnel fires is particularly important.

In recent years, combined smoke exhaust has gradually become the mainstay of tunnel fire prevention and control, and it has been widely applied in the construction of long-distance tunnels. To this end, scholars at home and abroad have carried out a large number of studies on this and achieved fruitful results. Ingason H et al.<sup>[2]</sup> studied the backflow length of smoke with different fire powers under the

action of longitudinal wind in the case of single-point and double-point centralized smoke exhaust, and established a prediction model. On this basis, Chen L F et al. [3] studied the influence of the distance between the ceiling smoke exhaust outlet and the fire source on the length of smoke backflow through a reduced-scale model, improved the prediction model, proposed a correction formula for the length of smoke backflow, and verified the accuracy of the formula by combining experimental data. However, this is only limited to the situation where the smoke exhaust outlet is located downstream of the fire source. Dai Yanming et al. [4] studied the influence of the distribution of smoke exhaust outlets on the temperature distribution of the smoke layer in the tunnel. With the gradual increase of the area and spacing of the smoke exhaust openings, the speed of smoke spread first increases and then gradually decreases, and the width-to-height ratio of the smoke exhaust openings has little influence on the spread of smoke. Yan et al. [5] used the numerical simulation method to study the smoke movement and control under the tunnel centralized smoke exhaust mode with different transverse fire source positions, smoke exhaust outlet sizes and smoke exhaust volumes. The elongated smoke exhaust outlets perpendicular to the longitudinal direction of the tunnel can control the smoke better than the short smoke exhaust outlets, especially in the area far away from the fire source. Jiang Xuepeng et al. [6] adopted the numerical simulation method to study the influence of different spacings, shapes, areas and distances from the vault on the thermophysical properties of the smoke layer at the smoke exhaust outlets. When the smoke exhaust outlets are located upstream, Li Lianjian [7] proposed a new characterization model and revealed the quantitative relationship between the Fr number and the Ri number and the stability of smoke stratification. Considering the situations where the comprehensive smoke exhaust outlets are located both upstream and downstream, Wang Junheng [8] analyzed the relationship between the mass flow rate of the smoke and the longitudinal wind speed, and established the corresponding prediction model. At the same time, Tang F et al. [9] analyzed the influence of longitudinal ventilation on the critical wind speed of smoke backflow in the tunnel, and proposed a prediction model for the critical wind speed of the coupling effect between top centralized smoke exhaust and longitudinal ventilation. Xu Haoduo et al. [10] used FDS to study the influence of the longitudinal wind speed on the effect of centralized smoke exhaust, and obtained the significant degree of the influence of longitudinal ventilation on the effect of tunnel centralized smoke exhaust through variance analysis. Qiu Qiaozhi et al. [11] analyzed the smoke exhaust effects of different smoke exhaust methods under the action of longitudinal wind by using FDS, and concluded that appropriately applying longitudinal wind can improve the smoke exhaust efficiency, and the combination with top centralized smoke exhaust has the best smoke exhaust effect.

In conclusion, regarding the relevant research on the synergistic effect of longitudinal ventilation and centralized smoke exhaust in tunnels, the current research mainly focuses on the combined study of unidirectional longitudinal ventilation and single-point and double-point smoke exhaust at the top. However, there is a lack of relevant research on the synergistic effect of bidirectional longitudinal ventilation and multiple smoke exhaust outlets at the top. Therefore, this paper mainly studies the control effect of the early-stage smoke in tunnel fires under the synergistic effect of bidirectional longitudinal ventilation in the tunnel and multiple continuous scattered exhaust outlets at the top. It can provide certain references for the prevention and control of smoke in highway tunnel fires, the evacuation of people, and emergency rescue.

## 2. Introduction to FDS

FDS is a software developed by the National Institute of Standards and Technology (NIST) in the United States, specifically designed for fire dynamic simulation (FDS). It is based on computational fluid dynamics and can simulate and predict the movement, temperature, and concentration of smoke, CO and other toxic gases in fires. The software can simulate a wide range of fires, from daily stoves, room fires to various fires caused by electrical equipment. It offers convenient and fast modeling and supports the import of model files in DXF and FDS formats. FDS is used to create fire simulations, effectively predicting the flow of fire smoke, fire temperature and the distribution of toxic and harmful gas concentrations. Based on the theory of computational fluid dynamics, the software simulates and

predicts the flow of smoke, CO and other toxic gases, fire temperature and the distribution of smoke concentration in fires. The software can simulate a wide range of fires, including daily stoves, room fires and various fires caused by electrical equipment.

### 3. Establishment of Fire Numerical Model

#### 3.1 Tunnel Geometry Model

In this paper, FDS is used to establish the tunnel geometric model as shown in Figure 1. The size of the tunnel model is 1100 m×15.25 m×6.0 m, and 12 outlet outlets are set downstream of the fire source. The size of a single outlet is 3.0 m×3.5 m×3.0 m, and the outlet is separated by a partition board. The distance between the bottom and the top of the model is 3 m, and the distance between the single outlet is 0.5 m. The outlet is located at 1000 m.

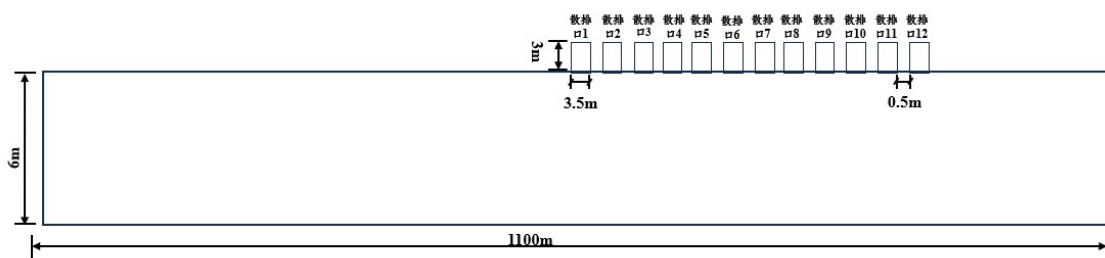


Figure 1. Tunnel model

#### 3.2 Setting fire Scenarios

The ambient temperature of the air and the wall in the tunnel is set to 20 °C, the property of CONCRETE is set to the tunnel wall, and the adiabatic boundary condition is set to the atmospheric pressure is  $1.013 \times 10^5 \text{ Pa}$ , the acceleration of gravity is  $9.8 \text{ m/s}^2$ , and the longitudinal wind speed at both ends of the tunnel inlet and outlet is set to 3.5 m/s. Since the highway tunnel is mainly used by large trucks, cars, buses and other vehicles, and the fire type is mainly large fires, the fire source power is set to 50 MW. Monitoring points for temperature, CO concentration, and visibility are set at a height of 2 m above the ground with an interval of 5 m. Sections for temperature, CO concentration, and visibility are set at the center line of the tunnel to observe the longitudinal distribution of flue gas components as shown in Figure 2.

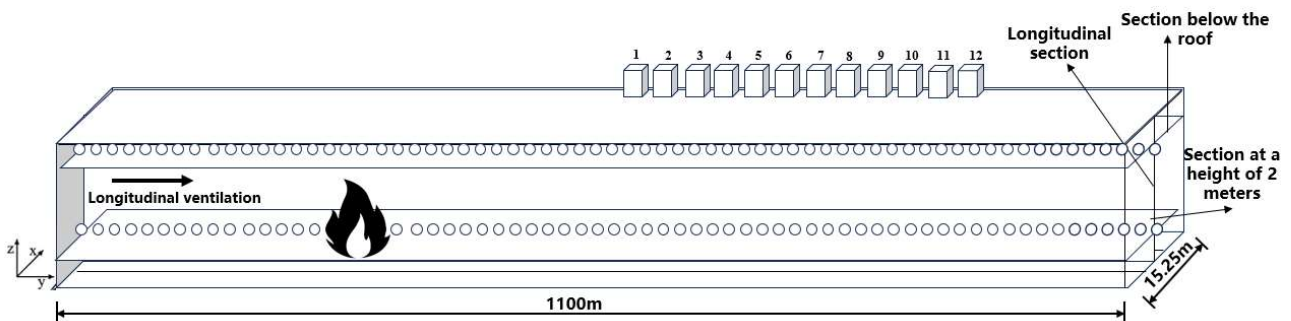


Figure 2. Tunnel model

In this study, the smoke exhaust volume of a single scattered exhaust outlet is set to be 10 m<sup>3</sup>/s, 20 m<sup>3</sup>/s, 30 m<sup>3</sup>/s, and 40 m<sup>3</sup>/s respectively, and the total smoke exhaust volumes are 120 m<sup>3</sup>/s, 240 m<sup>3</sup>/s, 360 m<sup>3</sup>/s, and 480 m<sup>3</sup>/s respectively. A total of 4 sets of simulation working conditions are set up for this purpose, as specifically shown in Table 1.

**Table 1.** Working condition table

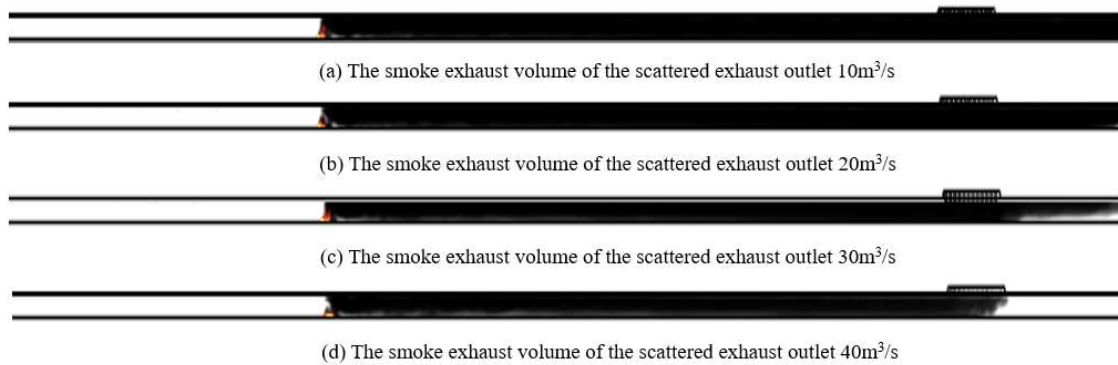
Working condition	Longitudinal wind speed (m/s)	Fire power (MW)	Single exhaust volume (m <sup>3</sup> .s-1)	Number of outlets (pieces)	Total smoke emission (m <sup>3</sup> .s-1)
1	3.5	50	10	12	120
2	3.5	50	20	12	240
3	3.5	50	30	12	360
4	3.5	50	40	12	480

## 4. Result Analysis

### 4.1 Fire Smoke Spread Analysis

Under different smoke exhaust volume conditions, after the fire smoke stabilizes, it is shown in Figure 3 below.

It can be seen from Figure 3(a) that when the single smoke exhaust volume of the scattered exhaust outlet is 10 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section after passing through the scattered exhaust outlet, and the smoke cannot be controlled. From Figure 3(b), it can be observed that when the single smoke exhaust volume of the scattered exhaust outlet is 20 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section after passing through the scattered exhaust outlet. However, there is a noticeable reduction in the amount of smoke compared to Figure 3(a), yet the smoke has not been brought under control. As shown in Figure 3(c), when the single smoke exhaust volume of the scattered exhaust outlet is 30 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section, but there is a significant decrease in the amount of smoke compared to Figure 3(b), and the smoke is still not under control. From Figure 3(d), it can be seen that when the single smoke exhaust volume of the scattered exhaust outlet is 40 m<sup>3</sup>/s, the smoke does not spread to the next smoke exhaust section, and the smoke is effectively controlled.



**Figure 3.** Longitudinal Spread Distribution Map of Smoke

### 4.2 Temperature Analysis

Under different smoke exhaust volume conditions, the longitudinal temperature distribution is shown in Figure 4. The temperature changes within a distance of 100 m downstream of the opened scattered exhaust outlet are shown in Figure 4.

It can be seen from Figure 4(a) that, with the combination of the longitudinal wind speed and the scattered exhaust outlet, when the single smoke exhaust volume of the opened scattered exhaust outlet is 10 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section after passing through the scattered exhaust outlet, and the smoke cannot be controlled. However, the temperature in the next section does

not exceed 60°C, which is within the safe range. This indicates that after the scattered exhaust outlet is opened, a single smoke exhaust volume of 10 m<sup>3</sup>/s is effective for controlling the temperature inside the tunnel. From Figure 4(b), it can be observed that when the single smoke exhaust volume of the opened scattered exhaust outlet is 20 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section after passing through the scattered exhaust outlet. However, there is a significant decrease in temperature compared to Figure 4(a). Although the smoke has not been controlled, the temperature in the next section does not exceed 60°C, which is within the safe range. This shows that after the scattered exhaust outlet is opened, a single smoke exhaust volume of 20 m<sup>3</sup>/s is effective for controlling the temperature inside the tunnel. As shown in Figure 4(c), when the single smoke exhaust volume of the opened scattered exhaust outlet is 30 m<sup>3</sup>/s, the smoke still spreads to the next smoke exhaust section, but there is a significant decrease in temperature compared to Figure 4(b). The smoke has not been controlled, yet the temperature in the next section does not exceed 60°C, which is within the safe range. This demonstrates that after the scattered exhaust outlet is opened, a single smoke exhaust volume of 30 m<sup>3</sup>/s is effective for controlling the temperature inside the tunnel. From Figure 4(d), it can be seen that when the single smoke exhaust volume of the opened scattered exhaust outlet is 40 m<sup>3</sup>/s, the smoke does not spread to the next smoke exhaust section, and the smoke is under control. The temperature in the next section does not exceed 60°C, indicating that after the scattered exhaust outlet is opened, a single smoke exhaust volume of 40 m<sup>3</sup>/s is effective for controlling the temperature inside the tunnel. By comparing Figure 4(a) to 4(d), it can be concluded that when the single smoke exhaust volume of the scattered exhaust outlet is 40 m<sup>3</sup>/s, it is the most effective for controlling the temperature inside the tunnel.

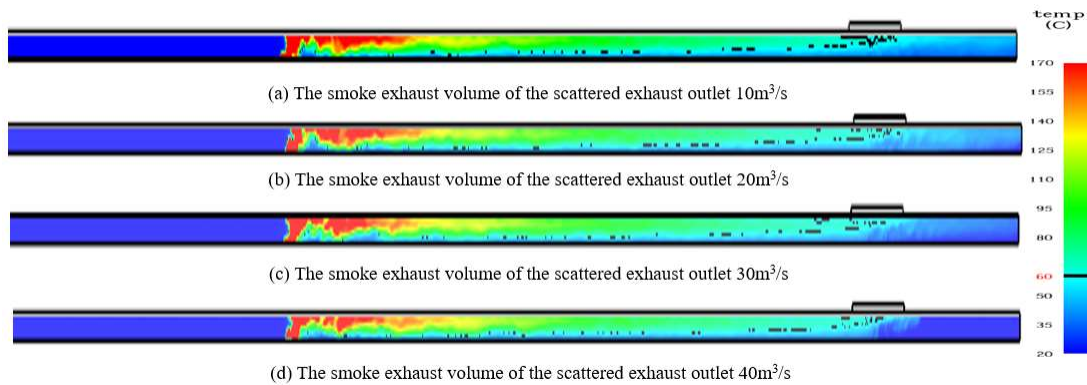


Figure 4. Longitudinal Distribution Map of Temperature

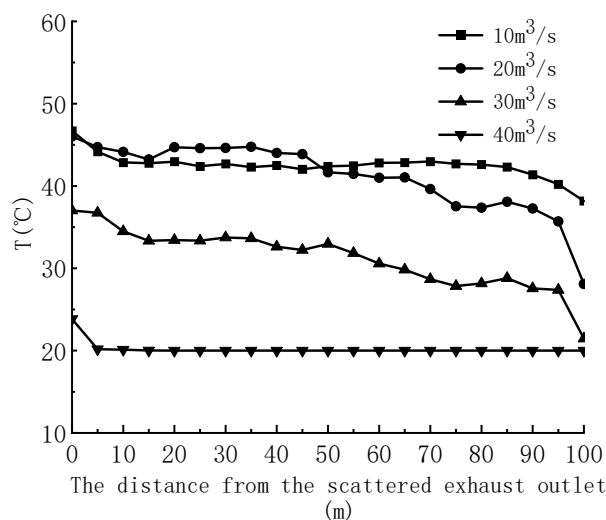


Figure 5. Graph of Temperature Changes within 100m Downstream of the Scattered Exhaust Outlet

It can be known from Figure 5 that, with the combination of the longitudinal wind speed and the scattered exhaust outlet, when the smoke exhaust volume of a single scattered exhaust outlet is 10 m<sup>3</sup>/s, the highest temperature within 100 m behind the scattered exhaust outlet reaches 46°C. The temperature change is the highest closest to the scattered exhaust outlet, but it is 26°C higher than the ambient temperature. When the smoke exhaust volume of a single scattered exhaust outlet is 20 m<sup>3</sup>/s, the highest temperature within 100 m behind the scattered exhaust outlet reaches 45°C, which is 25°C higher than the ambient temperature. The downward trend of the temperature is because, under the effect of a relatively large smoke exhaust volume, the smoke exhaust outlet will absorb a large amount of smoke and attract cold air to flow in, thus reducing the surrounding temperature. When the smoke exhaust volume of a single scattered exhaust outlet is 30 m<sup>3</sup>/s, the highest temperature within 100 m behind the scattered exhaust outlet reaches 38°C, which is 18°C higher than the ambient temperature. The downward trend of the temperature is also due to the fact that, with a large smoke exhaust volume, the smoke exhaust outlet will absorb a large amount of smoke and draw in cold air, thereby reducing the surrounding temperature. When the smoke exhaust volume of a single scattered exhaust outlet is 40 m<sup>3</sup>/s, the temperature at the height of personnel at 100 m behind the scattered exhaust outlet basically remains at the ambient temperature, indicating that the control effect on the smoke temperature is relatively good. This is because, under the action of a large smoke exhaust volume, the smoke exhaust outlet will absorb a large amount of smoke and attract cold air to flow in, thus reducing the surrounding temperature. Under the coordinated action of the longitudinal wind and the scattered exhaust outlet, the temperature field in the second smoke exhaust section does not pose a great threat to personnel.

### 4.3 Analysis of CO Concentration

Under different smoke exhaust volume conditions, the longitudinal distribution of CO concentration is shown in Figure 6. The variation of CO concentration within a distance of 100 meters downstream of the opened scattered exhaust outlet is also shown in Figure 6.

It can be seen from Figure 6 that, with the combination of the longitudinal wind speed and the scattered exhaust outlets, the smoke will not flow back, and the CO concentration upstream of the fire source is lower than the critical dangerous value. According to the longitudinal distribution of the CO concentration changes in the tunnel, it can be observed that the distribution of the CO concentration downstream of the fire source in front of the scattered exhaust outlets is similar. As the smoke exhaust volume increases from 10 m<sup>3</sup>/s to 40 m<sup>3</sup>/s, the smoke exhaust capacity at the position of the scattered exhaust outlets is enhanced. When the smoke exhaust volume reaches 40 m<sup>3</sup>/s, the smoke can be controlled once it spreads to the scattered exhaust outlets downstream and will not spread to the next smoke exhaust section. By comparing Figure 6(a) to 6(d), it can be concluded that when the smoke exhaust volume of a single scattered exhaust outlet is 40 m<sup>3</sup>/s, it is the most effective for controlling the temperature inside the tunnel.

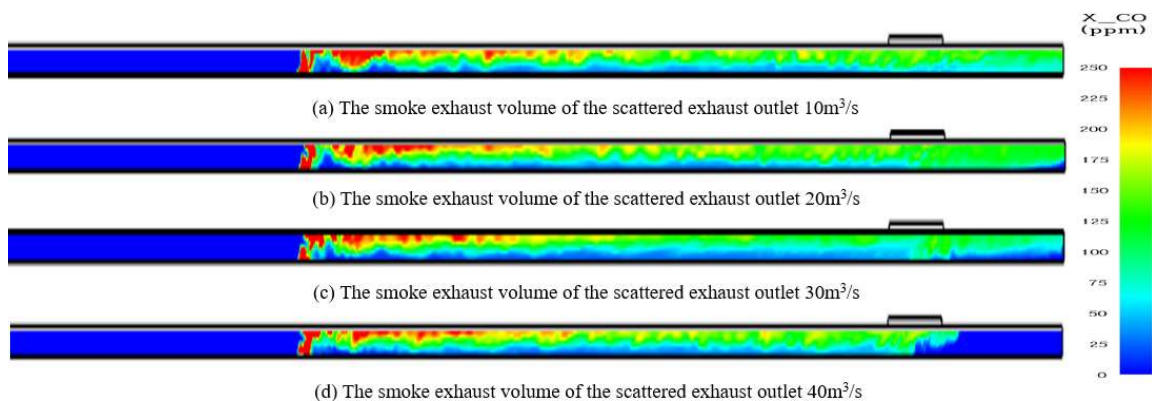
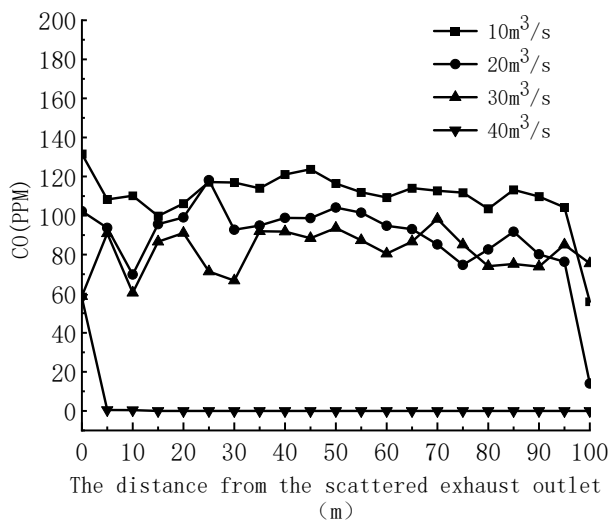


Figure 6. Longitudinal Distribution Map of CO Concentration



**Figure 7.** Graph of CO Concentration Changes within 100m Behind the Scattered Exhaust Outlet

It can be known from Figure 7 that, with the combination of the longitudinal wind speed and the scattered exhaust outlet, when the smoke exhaust volume of a single scattered exhaust outlet is 10 m<sup>3</sup>/s, the highest CO concentration within 100 m behind the scattered exhaust outlet reaches 135 PPM. The change in CO concentration is the highest closest to the scattered exhaust outlet, but it is lower than the critical dangerous value. When the smoke exhaust volume of a single scattered exhaust outlet is 20 m<sup>3</sup>/s, the highest CO concentration within 100 m behind the scattered exhaust outlet reaches 120 PPM, which is also lower than the critical dangerous value. When the smoke exhaust volume of a single scattered exhaust outlet is 30 m<sup>3</sup>/s, the highest CO concentration within 100 m behind the scattered exhaust outlet reaches 100 PPM, still lower than the critical dangerous value. When the smoke exhaust volume of a single scattered exhaust outlet is 40 m<sup>3</sup>/s, the CO concentration at the height of personnel at 100 m behind the scattered exhaust outlet basically remains at the ambient CO concentration level, indicating that the control effect on the smoke temperature is relatively good. Therefore, under the coordinated action of the longitudinal wind and the scattered exhaust outlet, the CO concentration field in the second smoke exhaust section does not pose a great threat to personnel.

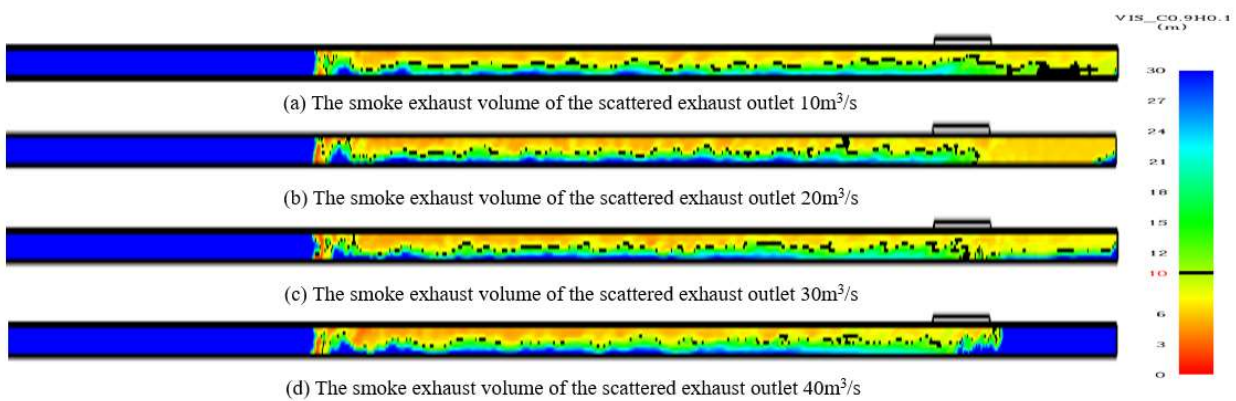
#### 4.4 Visibility Analysis

Under different smoke exhaust volume conditions, the longitudinal distribution of visibility is shown in Figure 8.

Under different smoke exhaust volume conditions, the longitudinal distribution of visibility is shown in Figure 8. It can be known from Figure 8 that the visibility distribution in the tunnel is basically consistent with the spread of smoke, and the distribution of smoke concentration can also be well characterized by the visibility. Under the action of the smoke exhaust outlets, the spread of smoke in the tunnel is obviously wavy. The smoke concentration is high where it accumulates on the tunnel roof, and the visibility is 0 m. The smoke concentration near the ground is low, and the visibility is 30 m (the blue area in the figure). This is because the density of smoke is lower than that of air, and restricted by the tunnel roof, the smoke will gather around the roof, resulting in the phenomenon of ceiling jet, which leads to high smoke concentration and low visibility at the roof.

With the combination of the longitudinal wind speed and the scattered exhaust outlet, when the smoke exhaust volume of a single scattered exhaust outlet is 10 m<sup>3</sup>/s, within 100 m behind the scattered exhaust outlet, the visibility exceeds the critical dangerous value (30 m). When the smoke exhaust volume of a single scattered exhaust outlet is 20 m<sup>3</sup>/s, within 100 m behind the scattered exhaust outlet, the visibility exceeds the critical dangerous value (30 m), but the effect is significantly better than that when the smoke exhaust volume is 10 m<sup>3</sup>/s. When the smoke exhaust volume of a single

scattered exhaust outlet is  $30 \text{ m}^3/\text{s}$ , within 100 m behind the scattered exhaust outlet, the visibility exceeds the critical dangerous value (30 m), and the effect is significantly better than that when the smoke exhaust volume is  $20 \text{ m}^3/\text{s}$  (the blue part downstream of the scattered exhaust outlet in the figure). When the smoke exhaust volume of a single scattered exhaust outlet is  $40 \text{ m}^3/\text{s}$ , the visibility at the height of personnel 100 m downstream of the scattered exhaust outlet basically remains at the ambient visibility level, indicating that the control effect on the smoke temperature is relatively good. Therefore, when the smoke exhaust volume of a single scattered exhaust outlet is  $40 \text{ m}^3/\text{s}$ , under the coordinated action of the longitudinal wind and the scattered exhaust outlet, the CO concentration field in the second smoke exhaust section will not pose a great threat to personnel.



**Figure 8.** Longitudinal Distribution Map of Visibility

## 5. Conclusion

- 1) Under the coordinated action of longitudinal ventilation and scattered exhaust outlets, it can effectively reduce the insufficient combustion of the fire source, decrease the generation amount of smoke, and also effectively lower the temperature, CO concentration and the thickness of the smoke layer inside the tunnel, providing strong support for ensuring the safety of people's lives and property.
- 2) When the number of scattered exhaust outlets is fixed, the higher the smoke exhaust volume of a single scattered exhaust outlet, the more effectively the spread of smoke can be controlled. When the smoke exhaust volume of a single scattered exhaust outlet is  $10 \text{ m}^3/\text{s}$ ,  $20 \text{ m}^3/\text{s}$ , or  $30 \text{ m}^3/\text{s}$ , there will be a great impact on the smoke exhaust effect, resulting in the inability to control the smoke, allowing the smoke to enter the second smoke exhaust section, which poses a serious threat to the evacuation and rescue of people. When the smoke exhaust volume is increased to  $40 \text{ m}^3/\text{s}$ , after the smoke passes through the scattered exhaust outlet, it does not spread to the next smoke exhaust section. The smoke is effectively controlled, which is conducive to the evacuation and rescue of people and
- 3) By setting a reasonable number of scattered exhaust outlets and smoke exhaust volume, the threat posed by the smoke from tunnel fires to people can be effectively reduced. Under the condition that there are 12 scattered exhaust outlets and the smoke exhaust volume of each individual outlet is  $40 \text{ m}^3/\text{s}$ , the effect of smoke control is relatively good, which is more conducive to the evacuation and rescue of people.

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