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# Study on the Coupled Smoke Characteristics and Evacuation of Underwater Immersed Tube in Tunnel Fire

**Yubo Luo[1,a], Haoxiang Li[2,*], Tongqing Wei[3,b], Jialin Ma[4,c]**

*[1]Central South University, Changsha, China*
*[2]City University of Hong Kong, Kowloon Town, Kowloon, Hong Kong, China*
*[3]The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*
*[4]Zhejiang Normal University, Jinhua, Zhejiang, China*
*[a]luo.yubo@qq.com, [b]weitongqing0601@outlook.com, [c]Lunapapa0912@163.com*
*[*]Corresponding author: haoxianli8-c@my.cityu.edu.hk*

***Abstract:*** *Fire accidents pose a great threat to the normal operation of underwater immersed tube tunnels, and failure to control or improper control will lead to serious disaster consequences. Based on the potential risks, this work explores the characteristics on the exhaust outlets and safety doors of underwater immersed tube tunnels from the smoke extraction and personnel evacuation. First, a one-way immersed tube tunnel was established by employing FDS numerical simulation software. And the characteristic parameters of smoke extraction in tunnel fire were analyzed by referring to the structural parameters of a certain domestic immersed tube tunnel. The longitudinal velocity and the exhaust outlet opening strategy were then analyzed. Finally, Pathfinder was used to simulating and calculating the required safe evacuation time ($T_{RSET}$), and through its comparison with the calculated available safe evacuation time ($T_{ASET}$), the optimal safety door spacing and width were determined, which is expected to provide a reference example for studying the coupled smoke extraction characteristics of underwater immersed tunnels fire.*

***Keywords:*** *Immersed Tube Tunnel; Numerical Simulation; Smoke Exhaust Strategy; Evacuation*

## 1. Introduction

In addition to the characteristics of ordinary tunnels, such as restricted space, a small number of entrances and exits, strong closure, etc. Underwater immersed tunnels are more difficult than road tunnels to ventilate, exhaust, and evacuate people due to the environmental complexity. Therefore, it is necessary to optimize the facilities' design, i.e., smoke exhaust characteristics, emergency evacuation of passengers, and traffic safety in underwater immersed tunnels.

Mechanical exhaust is mostly used in smoke control in tunnel engineering. Zeng et al. [1] analyzed the influence of ventilation mode and fire source location on the temperature distribution by establishing a scale model of the railway tunnel. Kurioka et al. [2] carried out tunnel fire tests with different sizes and obtained a prediction model for the maximum temperature of the tunnel fire. Oka et al. [3] conducted experimental research on the critical velocity by establishing a scale model and established critical velocity models with various size burners. Jin et al. [4] proposed the dimming coefficient and obtained the dimming coefficient expression and the personnel moving speed under different dimming coefficients. Milke [5] analyzed the evacuation behavior characteristics of people when the CO concentration was different and obtained the influence of CO concentration on the evacuated personnel. Bryan [6] found that people will make some behaviors closely related to human factors before escaping through the data analysis of fire investigation, such as decision-making, identification, reaction, judgment, etc. Luan [7] showed through simulation experiments that opening the smoke outlet around the fire source is conducive to smoke exhaust, while the distance between the smoke outlet and the fire source is large, which is not conducive to smoke exhaust. Zeng [8] and others studied and analyzed the smoke spread law and visibility under different wind speeds for large longitudinal slope tunnels and took the critical wind speed as a necessary indicator in the tunnel ventilation and smoke exhaust system. Xu et al. [9] took the two-way and six-lane immersed tunnel as the research object and analyzed the temperature field inside the tunnel. Xu et al. [10] and others obtained the design parameters of the evacuation and rescue channel of the Hangzhou River Crossing Tunnel through research and analysis on the factors affecting the safe evacuation of personnel, which provided an important basis for the fire safety design of the underwater tunnel. Fang et al. [11] and others took Shanghai Yangtze River Tunnel as the research object, carried out numerical simulation research on personnel evacuation and fire process. Li et al. [12] used empirical theory to study the relationship between the utilization rate of tunnel cross-channel and personnel evacuation behavior.

At present, the research on disaster prevention and mitigation of mountain and highway tunnels in China is relatively mature, while for two-way and eight-lane underwater immersed tunnels, there are relatively few collaborative studies on smoke exhaust strategies and emergency evacuation of drivers and passengers in tunnel fire. Based on this, this work will start from the two aspects of smoke exhaust and evacuation in underwater immersed tube tunnels. Through numerical simulation methods, the longitudinal velocity of the opening and closing strategy of smoke exhaust ports as well as the key parameters of safety gates on smoke exhaust and safety in large-section immersed tube tunnels is analyzed. This work is expected to provide a reference for the formulation of norms and related scientific research.

## 2. Determining coupled smoke extraction strategies

### *2.1. Description of the immersed tube tunnel structure*

The underwater immersed tube tunnel adopts a double-hole form, with two-way eight lanes on both sides, and a comprehensive pipe gallery in the middle. The upper, middle, and lower layers of the comprehensive pipe gallery are smoke exhaust passages, emergency passages, and cable trenches, respectively. The design vehicle speed is 120 km/h, the width of each lane is 3.75 m, the lateral widths of the left and right sides are 0.75 m and 1.25 m, respectively. And the left and right access roads (sidewalks) are 1 m respectively. The net width of the carriageway in one direction is 19 m, the net height is 8 m, the width of the emergency passage is 2 m, the height is 3.25 m, the length of each pipe section is 165 m. The sidewalls of the tunnel are equipped with smoke vents, the area of each vent is 6 m². The cross-section of the immersed tube tunnel is shown in Fig. 1. The engineering structure of the two-way and eight-lane immersed tube tunnel is complex and makes smoke evacuation difficult. The tunnel is proposed to use longitudinal ventilation and lateral centralized smoke evacuation so that the smoke will be evacuated by opening the smoke vent around the fire source in tunnel fire.

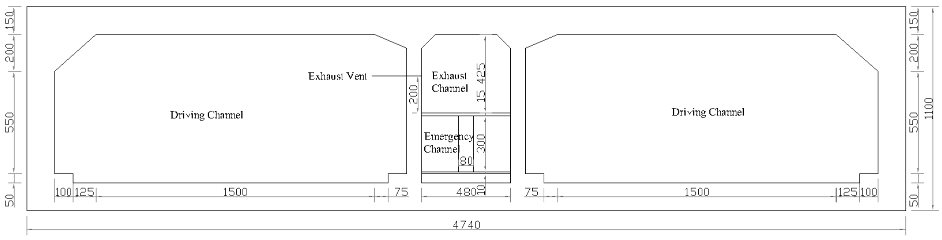


*Figure 1: Cross-sectional view of the underwater immersed tube.*

### *2.2. Determining the key parameters of the smoke outlet*

The FDS (Fire Dynamics Simulator, V6.1) software was used to carry out numerical simulation analysis on the spread law of fire smoke in this underwater immersed tunnel. The smoke extraction efficiency is obtained by varying the aspect ratio and the spacing of the smoke extraction outlet on the premise of determining the area of the smoke extraction openings. The numerical model is established according to the underwater immersed tube tunnel at a scale of 1:1, and the longitudinal length of the model is 1000 m. The main structure is a concrete structure with the air supply surface set in the left-hand opening of the tunnel model and the open surface set on the right-hand side. Both ends of the exhaust channel are set as exhaust surfaces so that the smoke can be drawn out. The overall model of the tunnel is shown in Fig. 2. When a large passenger car fires, the fire heat release rate is between 10-30 MW, and when an oil truck fire occurs, the fire heat release rate is between 30-100 MW. In “Overview of the Current Situation of Tunnel Fire and Fire Protection Technology at Home and Abroad”, the fire scale of a heavy vehicle fire is designed between 50-100 MW. Considering that, the proportion of large vehicles passing through the tunnel is low when a fire occurs and large vehicles occur in the tunnel. The probability of fire is small, so the design fire load is 50 MW. According to the theoretical calculation value of the amount of smoke generated, combined with the “Code for Fire Protection Design of

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Buildings" (GB50016-2014) (the full pressure of the exhaust fan should meet the requirements of the most unfavorable loop of the exhaust system. The amount of smoke should consider 10% to 20% of the air leakage). Therefore, after considering about 20% of the air leakage in this work, the calculated smoke exhaust volume is 260 m³/s. The ambient temperature is set to 20 °C, simulation duration is 1800 s. The mesh division in FDS numerical simulation will affect the simulation results. The smaller the mesh division size, the higher the simulation accuracy, but the longer the numerical simulation calculation time is. Through calculation and analysis, the grid size in this simulation is 0.5 m × 0.5 m × 0.5 m.

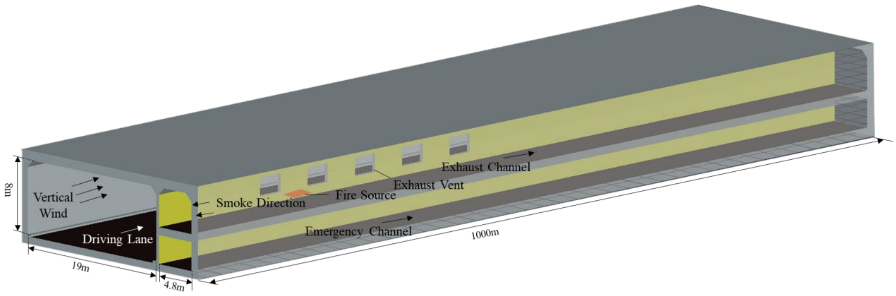


*Figure 2: FDS model of the underwater immersed tube.*

To determine the reasonable smoke vent spacing and size in the above underwater immersed tunnel smoke venting scheme, three smoke vent sizes (2×3, 3×2, 4×1.5 [L×H, m]) and three smoke vent spacings (40, 50, 60 [m]) were set up for a total of nine simulated conditions (A01~A09), as shown in Table 1. And set the fire source with a power of 50 MW in the middle of the tunnel model travel lane, and open 3 smoke exhaust ports upstream and 3 smoke exhaust ports downstream of the fire source at the same time, and set the longitudinal velocity to 0 m/s.

*Table 1: Numerical simulation conditions for exhaust light under fire load 50MW.*

| Number | Longitudinal Velocity (m/s) | Fire load (MW) | Exhaust (m³/s) | Exhaust vent size(L×H, [m]) | Exhaust vent spacing (m) | Number of opens |
|---|---|---|---|---|---|---|
| A01 ~ A03 | 0 | 50 | 260 | 2×3 | 40, 50, 60 | 3 upstream, 3 downstream |
| A04 ~ A06 | | | | 3×2 | 40, 50, 60 | |
| A07 ~ A09 | | | | 4×1.5 | 40, 50, 60 | |

Three main indicators affect the available safe evacuation time: the temperature in the tunnel at a height of 2 m above the ground is greater than 60°C, the visibility is less than 10 m and the CO concentration is greater than 500 ppm, which means that a dangerous state has been reached. Therefore, it is necessary to focus on the analysis of the above three indicators.

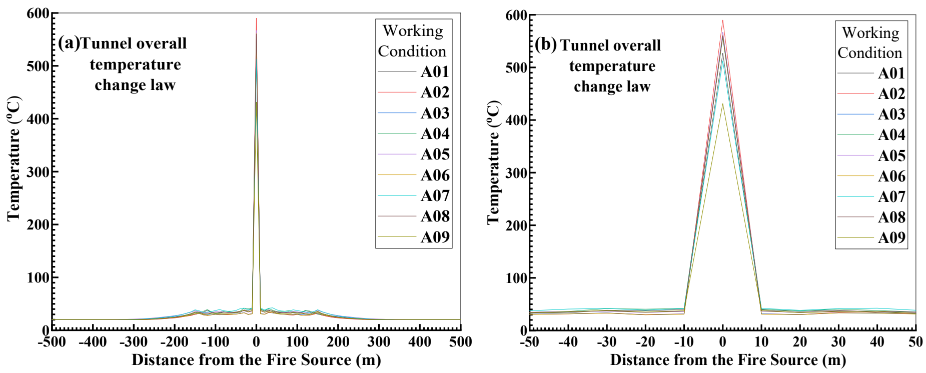


*Figure 3: Temperature change law of ground from the 2 m height.*

Fig. 3 shows the temperature change law after stabilization at a height of 2 m above the ground under different working conditions. It can be concluded that the temperature distribution law at a height of 2 m above the ground is the same in the lateral smoke exhaust mode. The temperature of the fire source at 2 m above the ground in the longitudinal direction of the tunnel is the highest, and the temperature gradually decreases as the distance from the fire source increases. The high-temperature area of the smoke in the longitudinal direction of the tunnel at a height of 2 m from the ground is distributed close to the fire source and decreases rapidly outside the range of 10 m from the fire source along both sides of the longitudinal direction. And is close to the ambient temperature (20°C), indicating that the stratification effect of the smoke in the tunnel space is better in the two-way balanced smoke exhaust mode, and the smoke can enter the exhaust duct through the smoke vent within a certain range. Comparing the working conditions A01~A09, it can be seen that the temperature distribution influence fluctuation range of 2 m high under different working conditions is within 200°C, but all of them are below 600°C, especially the temperature of working conditions A08~A09 at 2 m high is lower, which corresponds to a better smoke exhaust effect.

1) Distribution law of visibility at 2 m height in the tunnel

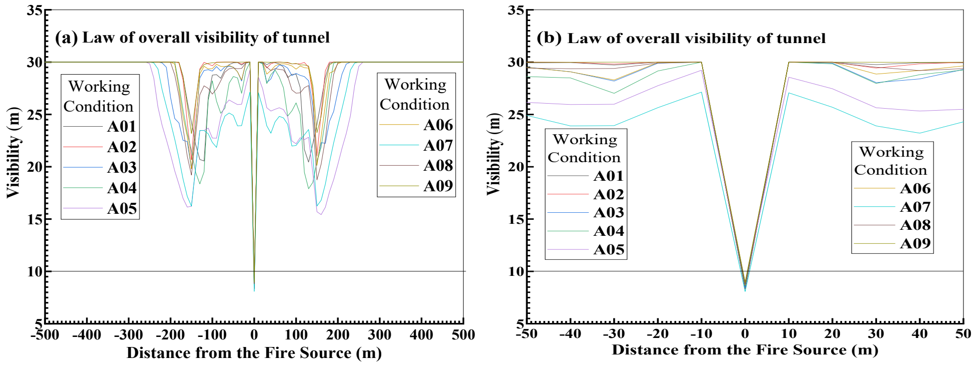


*Figure 4: Visibility change of ground from the 2 m height after stability.*

From the graph of visibility variation at 2 m height in the tunnel (Fig. 4), it can be seen that the visibility distribution pattern at 2 m height from the ground is the same in the two-way smoke exhaust mode. In all working conditions, the visibility within 5 m near the fire source is low, below 10 m. The longitudinal visibility of the tunnel at a height of 2m from the ground changes significantly in the area within the opening range of the smoke vent, and the visibility increases significantly near the smoke vent because the smoke enters the exhaust duct from the smoke vent, indicating that the smoke extraction effect is better in the centralized smoke extraction mode. Compared with the above working conditions, it is found that the visibility is greater than 10m outside the 10m range around the fire source, and the smoke exhaust effect is good.

2) Variation pattern of CO concentration at a height of 2 m in the tunnel

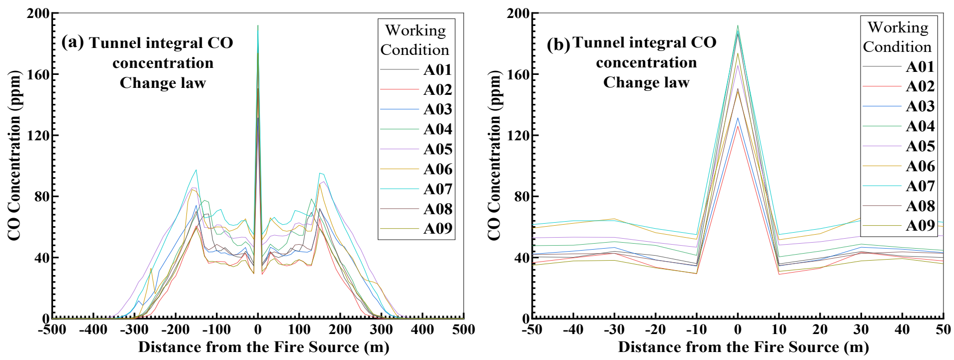


*Figure 5: CO concentration changes of ground from the 2 m height of working condition A08 (left), diagram near fire source (right).*

Figure 5 gives the graph of CO concentration variation at 2 m height of the tunnel. It can be concluded that the distribution pattern of CO concentration at 2 m height from the ground is the same for the two-way smoke exhaust mode. In all working conditions, the CO concentration within 10m near the fire source varied drastically and rose relatively fast, but none of them reached the critical danger value (500ppm) due to the good design value of smoke emission. Because the fire source power is large (50MW), the combustion is sufficient, and the designed smoke exhaust amount meets the actual value. Thus, with the increase of the exhaust amount, the maximum value of CO concentration in the tunnel does not change much. Comparing the above working conditions, it can be seen that the CO concentration distribution at 2m high with different exhaust volume fluctuates within the range of 100ppm, and none of them reaches the critical danger value, but the CO concentration of working conditions A02, A03 and A08 is relatively low, which also corresponds to a relatively small danger.

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*Table 2: Analysis of exhaust efficiency of the exhaust vent.*

| Number | Fire source power (MW) | Exhaust ($m^3/s$) | Percentage of smoke exhaust vent (%) | | | | | | Sum |
|---|---|---|---|---|---|---|---|---|---|
| | | | H1 | H2 | H3 | H4 | H5 | H6 | |
| A01 | 50 | 260 | 12.45 | 9.96 | 10.42 | 10.37 | 9.81 | 12.40 | 65.41 |
| A02 | | | 12.67 | 7.28 | 6.77 | 6.69 | 7.24 | 12.69 | 53.34 |
| A03 | | | 11.40 | 6.23 | 6.27 | 6.05 | 6.05 | 11.08 | 47.08 |
| A04 | | | 12.75 | 10.45 | 10.40 | 10.57 | 10.39 | 12.98 | 67.54 |
| A05 | | | 14.10 | 8.38 | 9.13 | 9.32 | 8.61 | 14.48 | 64.02 |
| A06 | | | 12.39 | 7.08 | 6.86 | 6.59 | 6.72 | 12.15 | 51.81 |
| A07 | | | 15.90 | 9.75 | 10.05 | 10.08 | 9.86 | 16.02 | 71.66 |
| A08 | | | 14.75 | 9.37 | 10.09 | 9.93 | 9.49 | 14.94 | 68.57 |
| A09 | | | 11.72 | 9.18 | 9.47 | 9.51 | 9.02 | 11.78 | 60.67 |

Table 2 shows the variation law of smoke exhaust efficiency under different smoke vent sizes and spacing. It can be found that in the lateral centralized smoke exhaust mode, the smoke exhaust efficiency gradually increases with the increase of the aspect ratio of the smoke exhaust port size. When the distance between the control smoke exhaust ports is certain and the smoke exhaust port size is the same, the smoke exhaust efficiency decreases with the increase of the smoke exhaust port distance. Among them, by comparing working condition A07 and working condition A08, i.e., the smoke vent size is 4 m × 1.5 m and the smoke vent spacing is 40 m and 50 m respectively, the smoke vent efficiency is not much different, and the comprehensive construction cost and smoke venting effect factors are determined that the smoke vent size of the underwater immersed tunnel is 4 m × 1.5 m and the smoke vent spacing is 50 m, which corresponds to working condition A08.

### *2.3. Longitudinal velocity and smoke exhaust coupling strategy*

By analyzing the variation characteristics of temperature, visibility and CO concentration at a height of 2 m from the bottom with different vent spacing and size, the key parameters of the optimal vent were determined. To further investigate the smoke exhaust efficiency under the influence of different longitudinal wind speeds and the coupling of smoke vent opening positions, four longitudinal wind speeds of 0, 1, 1.5, and 2 m/s and three smoke vent opening strategies were set, and 12 experimental conditions are shown in Table 3.

*Table 3: Different longitudinal velocity and exhaust vent mode coupling strategic conditions.*

| Number | Longitudinal Velocity (m/s) | Mode of opens |
|---|---|---|
| B01 | 0 | 1 upstream, 5 downstream |
| B02 | | 2 upstream, 3 downstream |
| B03 | | 3 upstream, 3downstream |
| B04 | 1 | 1 upstream, 5 downstream |
| B05 | | 2 upstream, 3 downstream |
| B06 | | 3 upstream, 3downstream |
| B07 | 1.5 | 1 upstream, 5 downstream |
| B08 | | 2 upstream, 3 downstream |
| B09 | | 3 upstream, 3downstream |
| B10 | 2 | 1 upstream, 5 downstream |
| B11 | | 2 upstream, 3 downstream |
| B12 | | 3 upstream, 3downstream |

Table 4 shows the smoke exhaust efficiency of smoke vents under different longitudinal airspeed and smoke vent opening mode coupling strategy conditions. It can be found that under the lateral centralized smoke exhaust mode, the smoke exhaust effect is higher than 60% for all working conditions, which can achieve a relatively good smoke control effect. Under the premise that the smoke vent spacing is 50 m and the vent size is 4 m × 1.5 m, the overall smoke exhaust efficiency of the tunnel is the highest when 2 smoke vents are opened upstream and 4 downstream, and the longitudinal wind speed is 1 m/s, which corresponds to working condition B05.

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*Table 4: Analysis of exhaust efficiency of the exhaust vent.*

| Number | Fire source power (MW) | Exhaust ($m^3/s$) | Percentage of smoke exhaust vent (%) | | | | | | Sum |
|---|---|---|---|---|---|---|---|---|---|
| | | | H1 | H2 | H3 | H4 | H5 | H6 | |
| B01 | 50 | 260 | 16.12 | 14.25 | 10.09 | 7.36 | 8.09 | 10.94 | 66.84 |
| B02 | | | 17.10 | 15.95 | 9.83 | 8.69 | 8.87 | 9.49 | 69.93 |
| B03 | | | 14.75 | 9.37 | 10.09 | 9.93 | 9.49 | 14.94 | 68.57 |
| B04 | | | 22.81 | 14.72 | 10.26 | 9.48 | 9.23 | 10.25 | 76.75 |
| B05 | | | 15.40 | 16.08 | 10.86 | 10.48 | 11.04 | 13.29 | 77.16 |
| B06 | | | 11.79 | 9.90 | 10.32 | 11.47 | 10.00 | 12.80 | 66.29 |
| B07 | | | 21.73 | 15.65 | 10.32 | 8.69 | 8.54 | 9.38 | 74.30 |
| B08 | | | 14.92 | 15.23 | 12.17 | 10.60 | 10.82 | 12.82 | 76.56 |
| B09 | | | 12.75 | 10.38 | 9.70 | 9.87 | 10.30 | 12.74 | 65.73 |
| B10 | | | 16.69 | 17.02 | 8.05 | 6.50 | 7.46 | 9.26 | 64.97 |
| B11 | | | 12.19 | 12.31 | 9.10 | 8.24 | 9.14 | 11.80 | 62.78 |
| B12 | | | 7.55 | 9.71 | 11.08 | 8.91 | 10.42 | 13.67 | 61.33 |

Further combining the three critical indicators that affect the available safe evacuation time: temperature greater than 60℃, visibility less than 10 m, and CO concentration greater than 500 ppm at a height of 2 m above ground level in the tunnel.

*Table 5: Safe available evacuation time of different working conditions.*

| Number | Longitudinal Velocity (m/s) | Mode of open | $T_{ASET}$ (s) |
|---|---|---|---|
| B01 | 0 | 1 upstream, 5 downstream | 331 |
| B02 | | 2 upstream, 3 downstream | 385 |
| B03 | | 3 upstream, 3downstream | 360 |
| B04 | 1 | 1 upstream, 5 downstream | 657 |
| B05 | | 2 upstream, 3 downstream | 750 |
| B06 | | 3 upstream, 3downstream | 817 |
| B07 | 1.5 | 1 upstream, 5 downstream | 435 |
| B08 | | 2 upstream, 3 downstream | 550 |
| B09 | | 3 upstream, 3downstream | 627 |
| B10 | 2 | 1 upstream, 5 downstream | 334 |
| B11 | | 2 upstream, 3 downstream | 346 |
| B12 | | 3 upstream, 3downstream | 362 |

Table 5 shows the safe available evacuation time under different working conditions. When the wind speed is 0 or 2m/s, the safe available evacuation time does not change much under different opening modes of smoke vents, and the safe available evacuation time is the shortest, fluctuating above and below 350s, at least 331s; when the wind speed is 1m/s, the safe available evacuation time is relatively the most, and the safe available evacuation time is the most when 3 smoke vents are opened both upstream and downstream, reaching 817s, which corresponds to working condition B06.

## 3. Conclusion

(1) The underwater tunnel designed this time adopts two-way and eight lanes. The tunnel adopts the

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cross-section of the two-hole single-pipe gallery, with lane holes on both sides. The net width of the one-way lane is 19 m and the net height is 8 m.

(2) FDS calculation software was used to establish a fire numerical simulation model for the underwater immersed tunnel, and by simulating the working conditions of different distances and different length-to-width ratios of the exhaust vents, it was found that the CO concentration changed drastically within 10 m near the fire source. The rise was relatively rapid but did not reach the critical hazard value (500 ppm). The temperature of the fire source at a height of 2 m from the ground in the tunnel is the highest, and the temperature gradually decreases with the increase of the distance from the fire source. In all working conditions, the visibility within 5 m near the fire source is low, less than 10 m, and the visibility in other places does not reach the critical dangerous value.

(3) By analyzing the exhaust efficiency of the exhaust port, it is determined that the size of the exhaust port is 4 m × 1.5 m, and the distance between the exhaust ports is 50 m. At the same time, it is found that the larger the aspect ratio of the exhaust port, the greater the exhaust efficiency.

(4) When the distance between the exhaust openings is 50 m and the size of the exhaust openings is 4 m × 1.5 m, the setting method of the exhaust openings is 2 openings upstream and 4 openings downstream, and when the longitudinal velocity is 1 m/s, the exhaust openings are most efficient. The cloud map of visibility, temperature, and CO concentration distribution in each working condition was analyzed, and the available time for safe evacuation was finally determined to be 331 seconds.

(5) Use Pathfinder software to model the lanes, the number of vehicles, and the number of people evacuated in the immersed tunnel, consider the most unfavorable situation, set the fire source at the safety gate, and change the width and spacing of the safety gate. Simulating personnel emergency evacuation, comprehensively considering the safety of personnel evacuation in the immersed tunnel, relevant specifications, and construction costs, the safety gate adopts a width of 2 m and a spacing of 80 m.

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