Numerical Study of Fire Smoke Exhausting in an Eight-lane Dual-Directional Rectangular Tunnel

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Abstract. In order to obtain the smoke exhausting characteristics of large-span cross section rectangular tunnel under lateral exhaust model, fire numerical simulation calculation was conducted by FDS to analyse the influence of different factors on smoke exhausting efficiency, including the layout, area, and spacing of smoke exhausting valves in immersed tunnels, and the applicability of the different tunnel width under the model of lateral exhaust was studied. The results are as follows: The smoke exhausting efficiency of individual exhausting valve decreases with more exhausting valves opened, but the total smoke exhausting efficiency of immersed tunnel increases. When three smoke exhausting valves are arranged in a group, the increase of distance between groups is conducive to smoke exhausting. The Smoke exhausting efficiency of evenly arranged valves is higher than the ones where three valves are in a group. When the number of exhausting valves opened remains the same, the increase of opening area can increase the total smoke exhausting efficiency because the ventilation resistance reduces. In lateral exhaust model, the increase of the width of immersed tunnel can result in the sharp decrease of smoke exhausting efficiency. In a two-lane, uni-directional immersed tunnel, the smoke exhausting efficiency is 93.7%, and that of a four-lane one is only 45.94%. For the poor applicability of lateral exhaust model in the large-span cross section immersed tunnel fire, it is suggested that additional smoke exhausting measures should be adopted to increase the efficiency of smoke exhausting.

1. Introduction

With the rapid development of tunnel engineering technology, domestic and foreign scholars have conducted many numerical simulations and experiments of fire on road tunnels, railway tunnels and underground tunnels, and a lot of progress has been achieved. However, most researches are concerned about the distribution of velocity, temperature, harmful gas concentration and visibility during the fire, only a few researches focus on the effectiveness and adaptability of smoke exhausting plans from the perspective of smoke exhausting efficiency. Zhu Hehua et al. has carried out numerical simulations and experiments of tunnel temperature field in different fire cases, especially the CFD analysis of smoke control on large-span cross section shield tunnel [1]. Xia Yongxu et al. conducts the optimization research on the outlet of smoke exhausting valves in road tunnels and makes some improvements on the calculating approach of fire ventilation [2]. Pan Yiping et al. analyzes the characteristics of fire in road tunnel on central smoke exhausting mode and carried out numerical simulations of smoke control [3]. Zhao Hongli et al. optimized the calculating method of road tunnel
ventilation network [4]. Liu Qi discusses the influence of exhaust rate change on smoke exhausting efficiency in central smoke exhausting system of road tunnel [5]. There are only a few smoke exhausting research of immersed tunnel fire. Wuhua optimizes the geometric parameters of the exhausting valves in the submarine tunnel of Hong Kong-Zhuhai-Macao Bridge, but his research is limited to the analysis of temperature, harmful gas concentration and visibility distribution within the tunnel. Moreover, the submarine tunnel of Hong Kong-Zhuhai-Macao Bridge is bi-directional six lanes [6]. For wider bi-directional eight-lane immersed tunnel, the relevant research of smoke exhausting in fire is hard to find. Applying numerical simulation, this work analyzes the smoke exhausting efficiency in bi-directional, eight-lane large-span cross section immersed tunnel fire and compares the adaptability of lateral exhaust in immersed tunnels of different width. The research results can provide reference for the similar smoke exhausting design of large-span cross section tunnel project.

2. Project Overview

This work is based on an immersed tunnel project. The tunnel is 6845 meters long, and the cross section is large-span adopting “two tunnels with one pipe gallery” design. The cross section of the whole tunnel is 46m wide and 10.6m high. The thickness of main structure slab is 1.5 m~1.7 m, Fig. 1 illustrates the cross section of the tunnel. The immersed tunnel is characterized by a large-span cross section, and the structure is flattened severely which increases the difficulty of ventilation and smoke exhausting during a tunnel fire. It is important to choose a reasonable and effective exhausting method. Considering the large-span cross section of immersed tunnel, this work adopts the traditional lateral exhaust model and conducts research on smoke exhausting efficiency of the different layout of exhausting valves and different lanes, aiming at analyzing the adaptability of lateral exhaust in large-span cross section immersed tunnel.

![Fig. 1 Cross Section of Eight-lane Dual-Directional Immersed Tunnel(cm)](image)

3. Calculating Model and Parameter Setting

3.1. Establishment of Model

The numerical calculation model of bi-directional eight-lane immersed tunnel is established by fire calculating software FDS, on condition that only a fire happens at the same time and the smoke doesn’t spread to the tunnel next to it. Therefore, the simulation is limited to the tunnel where the fire happened. A 15 m² longitudinal smoke exhausting channel is placed between two tunnels. There are three smoke exhausting valves in a lateral exhaust group, which connect the main tunnel and longitudinal smoke exhausting channel.

During the fire, the temperature of smoke and concentration of harmful gas around the fire source change dramatically. According to previous experience, smoke exhausting valves within 300m of the fire source are opened to exhaust smoke. Considering the influence of boundary condition on tunnel flow field, the numerical calculation model for immersed tunnel of 500 meters long is established.
3.2. Grid Setting
The accuracy of fire numerical simulation calculation increases with the decrease of the grid size. A lot of researches prove that the grid size should be 10% of fire characteristic diameter in numerical simulation calculation [7]. Because the area nearby the fire source is sensitive to grid density of numerical simulation, so the density of calculating grid in this area should be increased. The model grid at y direction (The longitudinal section) is 0.5m; the grid within 50m of fire source is 0.25m; the grid of the other two directions is 0.25m. The amount of grid in this model is 2,490,000.

3.3. Setting of Fire Source
This work mainly analyses from the developing stage of fire to the maximum HRR stage, without considering the attenuation stage [8]. The fuel is set as heptane, and its burning characteristic is default value in FDS database. The maximum HRR is set as 50MW. The burning surface is 1m high and placed in the middle of the tunnel longitudinal and horizontally. According to the characteristics of immersed tunnel, the total volume of exhausting smoke is 189 m³/s, and the air leakage of smoke exhausting system and the loss of resistance along the way are taken into consideration.

3.4. Boundary Condition and Parameters Setting
The boundary condition of fire numerical simulation calculation in immersed tunnel and other settings are depicted in Table 1

| Specification                        | Value       |
|--------------------------------------|-------------|
| HRR                                  | 50 MW       |
| Burning material                     | HEPTANE     |
| Area of burning surface              | 20 m²       |
| Starting time of smoke exhausting    | 90 s        |
| Width of tunnel                      | 18.3 m      |
| Height of tunnel                     | 6.7 m       |

3.5. Calculation of Working Conditions
When the total volume of exhausting smoke is 189 m³/s and the maximum HRR is 50MW, the smoke exhausting efficiency under different conditions of fire are calculated and the results are depicted in Table 2.

| Specification | Parameters of smoke exhausting valves |
|---------------|---------------------------------------|
| No.1          | Distance(m)  | Group/number | Width(m) |
| No.2          | 55           | 4/12         | 1        |
| No.3          | 55           | 6/18         | 1        |
| No.4          | 75           | 4/12         | 1        |
| No.5          | 90           | 4/12         | 1        |
| No.6          | 55           | 4/12         | 1.4      |
| No.7          | 55           | 6/18         | 1.4      |
| No.8          | 20           | 12 (Evenly arranged) | 1 |
| No.8          | 30           | 12 (Evenly arranged) | 1 |

4. Calculating Model of Smoke Exhausting Efficiency
The smoke exhausting efficiency of each exhausting valve is the percentage of the smoke exhausted from the exhausting valve per unit time to the total amount of smoke generated by the fire. The total smoke exhausting efficiency of smoke exhausting system is the percentage of the smoke exhausted
from the exhausting system per unit time to the total amount of smoke generated by the fire. That is to say, it is the sum of smoke exhausting efficiency of all exhausting valves [9].

The total amount of CO generated by the fire indicates the total amount of smoke generated by the fire, and the CO exhausted from each exhausting valve indicates the amount of smoke exhausted from each exhausting valve. Under the 50MW fire condition, the CO production of unit time is 6.579g/s theoretically. The exhausted amount of CO from each exhausting valve could be obtained by numerical simulation.

5. Result and Analysis

5.1. The Number of Unclosed Exhausting Valves

In a four-lane tunnel where the distance between smoke exhausting group was 55 m, 4 groups (12) and 6 groups (18) of exhausting valves were opened respectively, and the calculation results are shown in Fig. 2 and Fig. 3.

![Fig. 2 Smoke Exhausting Efficiency of Different Unclosed Exhausting Valves](image1)

![Fig. 3 Distribution of Smoke Exhausting Efficiency under Different Unclosed Exhausting Valves](image2)

Smoke exhausting efficiency of each group on both sides of the fire is roughly symmetrical, and the ones near the fire source are the highest. As the distance from the fire increases, the smoke exhausting efficiency decreases gradually. When the distance between each group and width of exhausting valve remain the same, increasing the number of opened valves results in the decrease of efficiency in separate groups, but the total efficiency of the smoke exhausting system increases. The reason why such phenomenon emerges can be interpreted as follows. The amount of total exhausting volume remains the same. When fewer exhausting valves are opened, the smoke flowing through each valve runs faster. Therefore, the ventilation resistance of exhausting valves increases, which is not conducive to smoke exhausting.

5.2. The Layout of Smoke Exhausting Valves Group

In a four-lane tunnel where 4 groups (12) of exhausting valves were opened and the distance between exhausting valves was 1m. The distance between smoke exhausting groups was 55m, 75m and 90m respectively, and the calculation results of different valve groups spacing are shown in Fig. 4.

Under the model of lateral exhaust, when exhausting valves are arranged in groups and each group consists of three valves, the smoke exhausting efficiency increases with the increase of spacing between groups. The smoke exhausting efficiency of 55m spacing is 45.94%; while that of 90m spacing is 47.05%. When the smoke exhausting arranged evenly, the smoke exhausting efficiency of 20m spacing is 51.48%, while that of 30m spacing is 49.75%. The Smoke exhausting efficiency of evenly arranged valves is higher than that of valves divided into three-valve groups.
5.3. The Area of Exhausting Valves

In a four-lane tunnel where the distance between smoke exhaust groups was 55m, the calculation results of different area of smoke exhausting valves opened are shown in Fig. 5.

According to the calculation results, when the distance between groups and the number of opened exhausting valves remains the same, the increase of the area of exhausting valve results in the increase of the smoke exhausting efficiency of single group and the total efficiency. When the area of exhausting valves increases, the smoke flowing through each valve runs slower. Therefore, the ventilation resistance of exhausting valves decreases, which is beneficial to smoke exhausting.

![Fig. 4 Smoke Exhausting Efficiency under Different Layouts of Exhausting Valves](image1)
![Fig. 5 Smoke Exhausting Efficiency under Different Exhausting Valves Areas](image2)

5.4. The Width of Immersed Tunnel

Under the two-lane condition, the influence of velocity is larger in the tunnel, which is beneficial to smoke exhausting. Because the influence of velocity is limited, the right area of four-lane tunnel is beyond the range being influenced. As a result, the slow velocity is not conducive to the horizontal flow of smoke in tunnel. When the width of immersed tunnel increases, the smoke exhausting efficiency decreases.

Under the model of lateral exhaust, the increase of the width in immersed tunnel results in the decrease of smoke exhausting efficiency. Lateral exhaust model works better in uni-directional two-lane tunnel and three-lane tunnel, but is not suitable for four-lane large-span cross section tunnel.

![Fig. 6 Velocity Distribution under Different Widths of Immersed Tunnel](image3)

6. Conclusions

This work studies the influence of different factors on the smoke exhausting efficiency of lateral exhaust model in different fire scene of large-span cross section immersed tunnel. The results are as follows:

1. If the amount of smoke exhausting valves being opened increases, the exhaust efficiency of individual exhausting valve will decrease. However, the efficiency of whole smoke exhausting system will increase, which is beneficial for exhausting smoke.
(2) When three smoke exhausting valves are arranged in a group, the increase of distance between groups will increase the efficiency of smoke exhausting system. The efficiency of evenly arranged smoke exhausting valves is higher than the ones where three valves are in a group.

(3) When the amount of smoke exhausting valves remains the same, the increase of opening area can increase the efficiency because the ventilation resistance is reduced.

(4) Under the model of lateral exhaust, the increase of the tunnel width reduces the efficiency of smoke exhausting. Lateral exhaust model works better in uni-directional two-lane tunnel and three-lane tunnel, but is not suitable for four-lane large-span cross section tunnel. Therefore, while designing the smoke exhausting system of large-span cross section immersed tunnel, additional smoke exhausting measures should be adopted to increase the efficiency of smoke exhausting in fire.

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