Study on smoke diffusion and ceiling temperature distribution in the V-shaped tunnel fire scenario

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Abstract:
In this paper, numerical simulations are conducted to study the smoke diffusion characteristics in the V-shaped slope tunnel with different slopes. The smoke diffusion characteristics and the ceiling temperature distribution with three kinds of heat release rates (HRR) and three kinds of slopes are considered without mechanical ventilation. The simulation results show that the smoke diffusion symmetrically on both sides of the symmetrical V-shaped tunnel. The smoke diffusion speed is mainly affected by the HRR, while it is less affected by the slope. The smoke diffusion speed increases with the increase of HRR. The maximum ceiling temperature increases with the increase of HRR and decreases with the increase of slope. The HRR is constant, the ceiling temperature decreases with the increase of the slope within 150 m away from fire source. Beyond 150 m from fire source, the ceiling temperature distribution are in opposite tendency and the overall temperature has a little difference between both sides of V-shaped tunnel.

Keywords: V-shaped slope tunnel; smoke spread characteristics; temperature beneath ceiling

1 Introduction

With the improvement of urbanization and the increase of the number of motor vehicles, the construction of more urban road tunnels has become an important choice for China's future urban transportation. In the process of urban road tunnel construction, it may be affected by various existing underground structures such as underground pipeline and subways. The vertical structure of underground tunnel is complex, no longer a simple horizontal or single-slope tunnel. For example V-shaped tunnels have been constructed for crossing rivers or existing subway lines. When a fire occurs in this kind of tunnel, the smoke diffusion would be different from those in the straight tunnel or single-slope tunnel. That is because of the different changes in the slope of the two sides of the V-shaped section. The smoke diffusion in the V-shaped tunnel need to be further studied for the smoke control system design and efficient operation.

Several researches have been done on the smoke diffusion characteristics and ceiling temperature on slope tunnel fires. Jiang[1] et al. studied the effect of competitive effect on smoke diffusion characteristics in V-shaped tunnels through numerical simulation. Merci[2] studied the factors affecting the stack effect of the tunnel. They concluded that the larger the slope is, the more obvious stack effect is. Oka et al.[3,4] studied ceiling jet in inclined tunnel fire through model experiment and numerical simulation. Smoke spreading characteristics and temperature distribution under different slopes were obtained. Liang Yi et.al.[5] improved the prediction model of ceiling temperature proposed by Kurioka[6] and proposed the prediction model of ceiling temperature in slope tunnel fire. Ji et al. [7] used numerical simulation software FDS to study the smoke diffusion characteristics in slope tunnel, obtained the distribution of smoke layer in slope tunnel. In the meantime, they established the prediction model of smoke temperature attenuation in slope tunnel.

The above studies mainly focus on temperature change in single-slope tunnels. However, few people have studied the smoke spreading in V-shaped tunnels. The smoke diffusion characteristics and ceiling temperature distributions in V-shaped tunnel and those in conventional inclined tunnel are different.

Therefore, the v-shaped tunnel fire scenarios with a variety of different working conditions would be studied through numerical simulation in this paper. The smoke diffusion and the ceiling temperature distribution under different slopes and different HRRs would be the key points. The research results are convinced to be useful for the smoke control in V-shaped tunnels.

2 Numerical simulation

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2.1 Physical model of tunnel

In this paper, the tunnel is 13m wide, 6.5 m high. The smoke extraction ducts is curved, the highest point is 2.0m, and the thickness of the top partition is 0.2m. The cross section of the tunnel is shown in Fig. 1, and the length of tunnel on each side of the V-shaped section studied in this paper is 400m. The fire source is located at the change point of the V-shaped tunnel. The fire source is set to be a volume heat source of 5m long, 3m wide and 1m high. The schematic of the tunnel is shown in Fig. 2.

![Fig. 1. Cross-section of the V-shape tunnel](image1)

![Fig. 2. Schematic diagram of tunnel](image2)

2.2 Numerical conditions

According to the actual slope condition of V-shaped underground tunnel, the slope at the entrance and exit of the tunnel is about 5% and the middle part slope is about 1%. In the area of underground structures such as subways, the slope is about 3%, so the slope values selected in this paper are 1%, 3% and 5% respectively.

Following the relative road tunnel design code[8,9], the HRR of cars is designed as 3 to 5 MW, and HRR of truck is designed as 10 to 15 MW, and HRR of bus is stipulated as 20 to 30 MW. The research object of this paper is urban road tunnel, the common fire HRRs are set as 10MW, 20MW and 30MW respectively. When the fire occurred in the tunnel due to the continuous collision of cars, HRR may be up to 50MW. This fire scenario has also been considered.

2.3 Meshing and boundary conditions

Following the grid setting regulation recommended in FDS User guide, the mesh size under 30MW fire source power is 0.23m~0.94m., the mesh size at 30MW HRR is 0.23m~0.94m. Fig.3 shows the ceiling temperature distribution with different mesh sizes. It can be seen from the figure that when the mesh size is larger to 1m, the ceiling temperature is higher, the mesh size is reduced, and the ceiling temperature is reduced. When the mesh size is 0.5m × 0.5m × 0.5m, its temperature distribution curve coincides almost exactly with the curve of the mesh size of 0.25m × 0.25m × 0.25m. The overall mesh size of this paper is set to 0.5m × 0.5m × 0.5m. In order to improve the calculation accuracy, the mesh encryption of 100m before and after the fire source is 0.25m×0.25m×0.25m. It is used to balance the calculation accuracy and calculation time.

No slip condition was used for the tunnel wall. Combustion reaction is considered to be rapid. The wall is set to be adiabatic. The tunnel roof partitions are made of concrete. The fuel is polyurethane.

![Fig. 3. The temperature distribution of the ceiling under different mesh sizes](image3)

3 Results and discussion

3.1 Smoke diffusion characteristics

Taking HRR of 30 MW and slope of 3% as an example, numerical smoke spread distances under different time are shown in Fig. 4. For the symmetrical V-shaped tunnel, it can be found that smoke diffuses symmetrically on both sides of the tunnel. Smoke diffusion distance increases with the time last.

![Fig. 4. Smoke diffusion under different fire burning time](image4)

Fig. 5 shows the smoke spreading velocity with different slope conditions at 30MW, and Fig. 6 shows the smoke spreading characteristics with different HRRs at the slope of 3%. The comparison of Figs. 5 and 6 specifically shows that when the HRR are the same, the smoke diffusion velocity at different slopes are same. When the slopes are the same, the smoke diffusion velocity under different HRR is significantly different. It can be clearly seen in Figure 6 that at the same distance from the fire, the higher the HRR, the faster the smoke diffusion velocity.

Thus it is found that the smoke diffusion velocity is mainly affected by the HRR, and is less affected by the slope. Under the same HRR, the smoke diffusion distance of tunnels with
different slopes have no obvious difference. This is because that with the small slope, the suction effect caused by stack effect is small. But because of the stratification effect of hot smoke and cold air is better, the front temperature of smoke is higher, so the diffusion velocity is faster. When the slope increases, the suction effect caused by the stack effect is enhanced, and the smoke flows faster, so that the convection heat transfer between hot smoke and cold air is strengthened. In the meantime, the smoke front temperature is reduced, and the diffusion rate is reduced. Therefore, there is little difference between the diffusion velocity of smoke and the small slope. With the same tunnel slope, the smoke diffusion velocity increases with the increase of HRR. At 10MW, the smoke diffuses to the whole computing domain at 500s; At 20MW, the smoke diffuses to the whole computing domain at 400s; At 30MW or larger, the smoke diffuses to the whole computing domain at 300s.

![Fig. 5. Smoke diffusion distance with different slopes at 30MW](image)

Fig. 5. Smoke diffusion distance with different slopes at 30MW

![Fig. 6. Smoke diffusion distances under different HRRs at 3% slope](image)

Fig. 6. Smoke diffusion distances under different HRRs at 3% slope

### 3.2 Ceiling temperature

The ceiling temperature measurement points are set at 0.2m below the top partition and 6.3m from the ground level. The maximum ceiling temperature is obtained above the fire source, and maximum ceiling temperature under different fire scenarios are shown in Table 1. The maximum ceiling temperature is found to increase with the HRR increasing and decrease with the increase of the slope. When the HRR is 50MW and slope is less than 5%, the maximum ceiling temperature reaches 1151℃, this might lead to the damage of the tunnel ceiling.

| slope | 10MW | 20MW | 30MW | 50MW |
|-------|------|------|------|------|
| 1%    | 426  | 675  | 996  | 1151 |
| 3%    | 349  | 640  | 841  | 1055 |
| 5%    | 319  | 590  | 651  | 775  |

Taking the results of HRR of 30 MW and the slope of 3% as an example, the longitudinal distribution of the ceiling temperature is shown in Figs 7 and 8. It can be seen that as the distance from the fire increases, the temperature gradually decreases. The farther away from the fire source position, the slower the temperature drops. HRR is found to have a great impact on the ceiling temperature. For the slope of 3%, the ceiling temperature increases with the increase of the HRR. At 30MV, within 150m from the fire source, the higher the slope is, the lower the temperature is. That is $T_{5\%} < T_{3\%} < T_{1\%}$. Beyond the fire source 150m, the temperature change law is different, and the overall temperature difference is not much.

![Fig. 7. The ceiling temperature distribution at 30MW](image)

Fig. 7. The ceiling temperature distribution at 30MW

![Fig. 8. The temperature distribution of the ceiling at the slope of 3%](image)

Fig. 8. The temperature distribution of the ceiling at the slope of 3%
4 Conclusion

Some spread under different fire scenarios in a symmetric V-shaped tunnel were studied by the numerical method in this paper, the effects of the fire HRR and the slope of the tunnel are considered. The main conclusions are as follows:

(1) For a symmetrical V-shaped tunnel, the smoke diffuses symmetrically on both sides of the tunnel, and the smoke diffusion distance is greatly affected by the HRR of the fire, and is less affected by the slope. Under the same tunnel slope, the smoke diffusion distance increases with the increase of the HRR; while under the same fire power, the smoke diffusion distance of tunnels with different slopes has no significant difference.

(2) As the distance from the fire source increases, the ceiling temperature gradually decreases. For the same slope, as the HRR increases, the temperature also increases. At the same HRR, within 150m away from the fire source, the ceiling temperature will decrease with the increase of the slope. Under the high fire power and the small slope of the tunnel, the maximum ceiling temperature would be very high, this might be dangerous for the tunnel ceiling, for control or smoke control should be sued for the structure safety.

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