Smoke Diffusion Characteristics of Continuous Tunnel Fire

Sha Tang*, Xiaoyang Han, Yansheng Zhi

CCCC Highway Consultants Co., Ltd., Beijing, 100120, China

*Corresponding author's e-mail: tangsha@ccccltd.cn

Abstract. To investigate the phenomenon of smoke spread between consecutive tunnel openings, this study employs STAR-CCM+ to establish a numerical simulation model of continuous tunnel fires. Various factors, including fire origin location, fire size, and longitudinal wind speed, are analyzed for their impact on smoke intrusion. The findings indicate that smaller fire sizes and larger distances between openings result in lower temperatures of smoke reaching the upstream tunnel exit. This leads to reduced buoyancy, causing the smoke to propagate longitudinally downstream further under the influence of horizontal inertial forces, thereby enhancing smoke intrusion. Additionally, lateral natural wind alters the trajectory of smoke flow, with higher lateral wind speeds corresponding to a more pronounced weakening of smoke intrusion. The objective of this research is to propose effective measures for the ventilation safety of continuous tunnel operation, ensuring the secure operation of vehicles and personnel in downstream tunnels.

Keywords: Continuous tunnel; Smoke infiltration; Numerical computation; Fire

1 Introduction

Due to the prevalence of mountainous terrain and complex topography in many regions, the conventional design approach for single tunnels becomes challenging. Consequently, on highway segments, there may be occurrences of consecutive tunnels with relatively short longitudinal intervals [1-4]. In the context of continuous tunnels, when a fire occurs in an upstream tunnel, the resulting smoke, under the influence of longitudinal ventilation, may disperse into the downstream tunnel, posing a threat to its safe operation. This phenomenon is referred to as smoke channeling.

Presently, many ventilation and smoke exhaust system designs still adhere to the conventional consideration of mutually independent single tunnels, neglecting the mutual influence of smoke in case of a fire in one tunnel on others. Addressing the issue of smoke diffusion during fires in continuous tunnels, Dong et al. [5] through theoretical analysis and numerical simulation, investigated the safety spacing when a fire occurs in consecutive tunnels. The results indicate that when there is no ventilation control in the upstream tunnel, the likelihood of smoke freely spreading and intruding into the downstream tunnel is minimal. With a critical wind speed applied upstream of the fire

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source and a fire size less than 30MW, the tunnel spacing can be set to greater than 100m. Wang et al. [6] conducted reduced-scale experiments to study three smoke intrusion patterns during fires in continuous tunnels. Zhao et al. [7] utilized FDS numerical simulation to analyze the impact of different wind velocity and adjacent tunnel spacing on fire-induced smoke intrusion, establishing a critical channeling wind velocity model. Although a limited number of domestic scholars have conducted relevant research, a comprehensive exploration of the influencing factors and patterns of smoke channeling during fires in continuous tunnels, such as the impact of fire source location and lateral natural wind, requires further investigation. This paper focuses on continuous tunnels, utilizing STAR-CCM+ to establish a numerical simulation model of continuous tunnel fires. Two assessment metrics, smoke channeling ratio (λ) and smoke diffusion angle (α) (the angle formed by the diffusion of smoke between the entrance of the downstream tunnel and the exit of the upstream tunnel to the atmosphere, referred to as the smoke diffusion angle), are introduced to analyze the impact of fire source location, fire size, and lateral natural wind velocity on smoke diffusion in continuous tunnel fires. The aim is to propose effective measures for the ventilation safety of continuous tunnel operation, ensuring the secure operation of vehicles and personnel in downstream tunnels.

2 Numerical Computational Method Establishment of Continuous Tunnel Fire Model

2.1 Geometric Model

Utilizing STAR-CCM+ software, we establish a computational model featuring an upper semicircular section (radius: 6m) and a lower rectangular section (height: 1.4m) for the tunnel profile, as depicted in Figure 1. The length of the upstream tunnel is set based on research conditions, fixing the downstream tunnel at 120m. The tunnel opening dimensions and external spaces are uniformly set to 60m. External tunnel slope is assumed as a vertically straight wall, and the area outside the opening is a flat surface, detailed in Figure 2. Fire sources, with heat release rates of 5MW, 20MW and 50MW, are positioned in the upstream tunnel. Inlet conditions include a velocity inlet boundary with a 3.5m/s longitudinal ventilation velocity, while the outlet is set as a pressure outlet boundary. Tunnel walls, mountain surfaces, and the ground are wall boundaries. The numerical domain interfaces with the atmospheric environment at an ambient temperature of 20°C, using a pressure outlet boundary for the domain interface. For lateral natural wind studies, corresponding interfaces are set as velocity inlet boundaries.

2.2 Grid Scale Analysis

In tunnel fire numerical simulations, mesh size significantly influences results, in which the characteristic diameter of the fire source is defined as shown in Equation 1. Based on the geometric model in Figures 1-2, simulations were conducted for the upstream tunnel with a length of 120m, tunnel spacing of 50m, with a centrally located fire source

(20MW), were conducted using varied grid sizes. The effects of these grid sizes on smoke concentration distribution in the upstream and downstream tunnels were illustrated in the Figure 3. To balance computational efficiency and accuracy, a grid size of 0.05D* was adopted near the fire source and the region of smoke dispersion between tunnel openings, while other regions inside and outside the tunnel used a grid size of 0.1D* (Figure 4).

$$D^* = \left(\frac{Q}{\rho_0 C_P T_0 \sqrt{g}} \right)^{\frac{2}{5}} \tag{1}$$

(1) Where: D* is the characteristic diameter of the fire source. Q is the fire heat release rate, kW.

2.3 Numerical Computational Method Validation

The experimental setup maintained a temperature of 30°C, featuring a scenario with a fire source positioned 0.65m from the tunnel entrance, a heat release rate of 2.54kW, a critical wind velocity of 0.53m/s, and a tunnel spacing of 0.3m. The computational model, established based on these conditions, was compared for temperature distribution (Figures 5-6). The minimal deviation between simulation and experimental results affirms the feasibility of utilizing STAR-CCM+ for numerical simulations in continuous tunnel fire research.

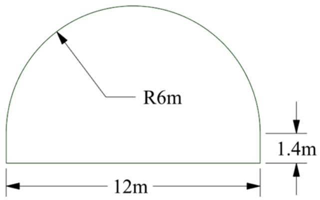


Fig. 1. Tunnel profile.

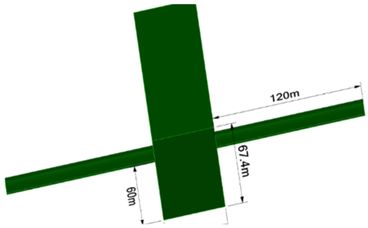


Fig. 2. Geometric model of continuous tunnel.

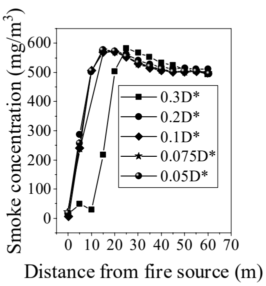


Fig. 3. Grid independence analysis.

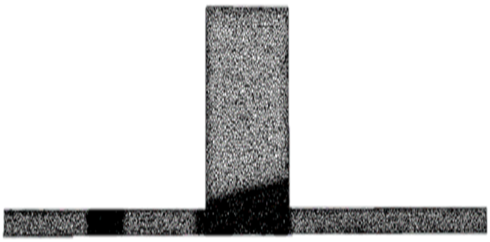


Fig. 4. Grid division.

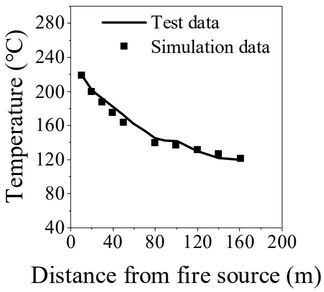


Fig. 5. Longitudinal temperature distribution of upstream tunnel.

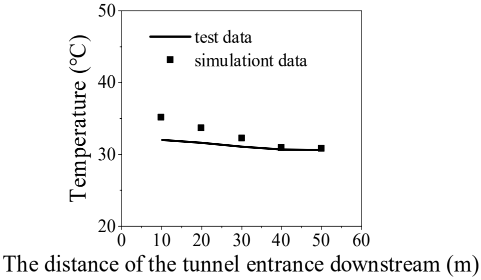


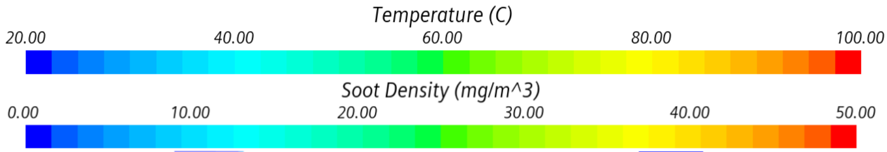
Fig. 6. Longitudinal temperature distribution of downstream tunnel.

3 Simulation Results and Discussion

Table 1. Conditions and simulation results

No.	Upstream wind velocity v_1 (m/s)	Distance between fire source and upstream tunnel exit (m)	Maximum channeling ratio λ_{max} (%)	Smoker diffusion Angle α (°)
1	3.50	60.00	17.85	44.00
2	3.50	150.00	26.35	41.50
3	3.50	600.00	38.05	39.50
4	3.50	1500.00	42.70	38.00
5	3.50	5000.00	47.60	0.00
6	3.50	5.00	17.81	42.50
7	3.50	50.00	17.82	46.00
8	3.50	0.50	36.50	39.50
9	3.50	1.00	8.60	39.52
10	3.50	1.50	0.00	39.55

The working conditions and simulation results of this study are shown in Table 1. According to the stability of the tunnel temperature field before and after stabilization, the smoke diffusion state can be categorized into the initial stage and the stable stage of the fire. Figures 7-10 depict the smoke distribution in Scenario 1. From Figures 7-8, during the initial stage of the fire, the smoke temperature in the upstream tunnel is elevated only at the fire source, while the temperature of the smoke at the exit is close to the ambient temperature. This diminishes the thermal buoyancy caused by temperature differences, causing some smoke to intrude into the downstream tunnel under the influence of horizontal inertial forces, with the maximum channeling ratio λmax occurring during the initial stage of the fire. As observed in Figures 9-10, after the temperature field stabilizes, the channeling phenomenon disappears, forming a stable diffusion angle. This is primarily because, after the temperature field stabilizes, the smoke reaching the tunnel exit has a significantly higher temperature than the surrounding ambient temperature, resulting in a substantial temperature difference between the exit smoke and the environment. Consequently, buoyancy forces have a pronounced effect on smoke flow, leading the smoke to vertically disperse into the atmospheric environment after leaving the upstream tunnel without intruding into the downstream tunnel.



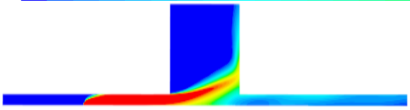


Fig. 7. Distribution of smoke concentration in the initial stage of fire (condition 1).

Fig. 8. Distribution of smoke temperature in the initial stage of fire (condition 1).

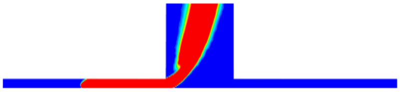


Fig. 9. Distribution of smoke concentration in the stable stage of fire (condition 1).

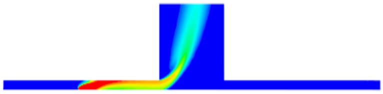
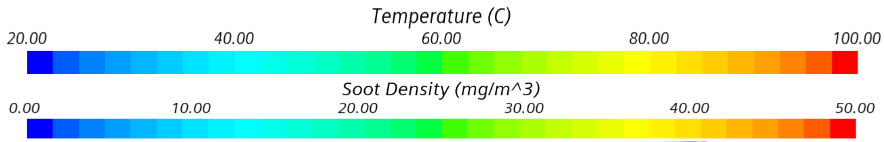


Fig. 10. Distribution of smoke temperature in the stable stage of fire (condition 1).

3.1 The Effect of Fire Source Location

The study investigated the impact of different fire source locations on smoke diffusion in continuous tunnel fires through scenarios 1-5. The computational results reveal that during the initial stage of the fire, phenomenon of channeling are observed in all scenarios. As the fire source distance from the upstream tunnel exit increases, the maximum channeling ratio λmax continuously rises. This is attributed to the increased cooling of smoke upon reaching the upstream exit with a greater distance from the fire source, leading to reduced buoyancy and enhanced intrusion under the influence of horizontal inertial forces. Simultaneously, as depicted in Figures 11-12, once the temperature field stabilizes, channeling phenomena disappear in all scenarios except for 5. Furthermore, the smoke diffusion angle decreases with the increasing distance of the fire source from the tunnel exit. For scenario 5, when this distance reaches 5000m, the smoke in the upstream tunnel has undergone extensive long-distance diffusion, experiencing substantial heat exchange and cooling. As a result, the temperature of the smoke at the upstream exit becomes comparable to the ambient temperature. At this point, a significant amount of low-temperature smoke is driven by horizontal inertial forces, intruding into the downstream tunnel.



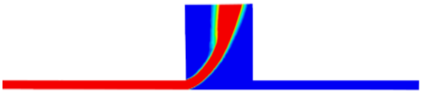


Fig. 11. Distribution of smoke concentration in the stable stage of fire (condition 3).

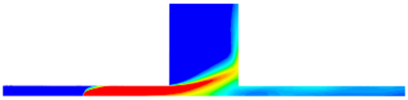


Fig. 12. Distribution of smoke concentration in the stable stage of fire (condition 6).

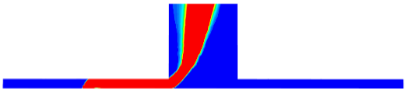


Fig. 13. Distribution of smoke concentration in the stable stage of fire (condition 7).

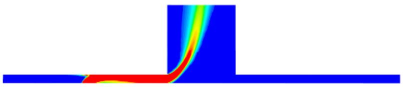


Fig. 14. Distribution of smoke temperature in the stable stage of fire (condition 7).

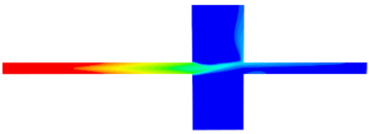


Fig. 15. Distribution of smoke concentration in the initial stage of fire (condition 9).

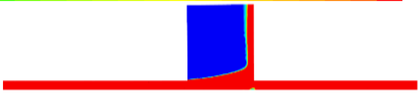


Fig. 16. Distribution of smoke concentration in the stable stage of fire (condition 5).

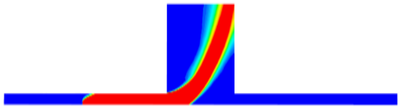


Fig. 17. Distribution of smoke concentration in the stable stage of fire (condition 6).

Fig. 18. Distribution of smoke temperature in the stable stage of fire (condition 6).

Fig. 19. Distribution of smoke concentration in the initial stage of fire (condition 7).

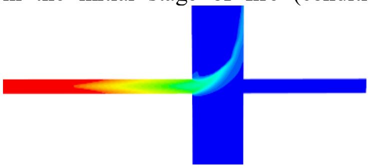


Fig. 20. Distribution of smoke concentration in the initial stage of fire (condition 10).

3.2 The Effect of Fire Power

The influence of fire power was examined through scenarios 1, 6 and 7, studying its impact on smoke diffusion in continuous tunnel fires. The data in Table 1 indicates that during the initial stage of the fire, all scenarios exhibit channeling phenomena with minimal variations in the maximum channeling ratio, as illustrated by the typical smoke distribution diagram in Figure 13. Upon stabilization of the temperature field, the smoke channel phenomena disappear, as depicted in typical distribution diagrams like those shown in Figures 14-15. Additionally, the smoke diffusion angle increases with the rise in heat release rate (HRR). This is elucidated by Figures 16-17, where an increase in HRR results in elevated temperatures of the smoke in the upstream tunnel, strengthening buoyancy forces. Consequently, the horizontal dispersion distance of smoke in the downstream direction is reduced, leading to an increase in the diffusion angle α.

3.3 The Effect of Lateral Natural Wind

The influence of lateral natural wind on smoke diffusion in continuous tunnel fires was studied in scenarios 8, 9 and 10. As observed in Figures 18-20, during the initial stage of the fire, the presence of lateral wind leads to a deviation in the trajectory of smoke flow, indicating a tendency to move away from the exit of the downstream tunnel. With increasing lateral wind velocity, the distance between the smoke and the exit of the downstream tunnel increases, resulting in a weakening of channeling. When the lateral wind reaches 1.5m/s, channeling disappears. It can be noted that after the temperature field stabilizes, due to the elevated temperature of the smoke between the openings, buoyancy forces become influential. Consequently, no channeling is observed in any scenario, and the values of the smoke diffusion angle are essentially identical.

Through the above numerical simulation results, further suggestions can be given in engineering design. For continuous tunnels, increasing the distance between two tunnels is undoubtedly the most effective measure. However, when geographical conditions do not allow, this paper believes that installing additional fans at the outlet of the upstream tunnel to simulate lateral natural wind is also a measure to reduce the influence of channeling.

4 Conclusion

In this study, a numerical computational model for continuous tunnel fires was established using STAR-CCM+. The analysis incorporated two metrics, namely the smoke channeling ratio and the smoke diffusion angle, to assess the impact of fire source location, fire size, and longitudinal wind speed on smoke intrusion. The main conclusions are as follows:

In the event of a fire in the upstream tunnel, smaller fire sizes and larger distances from the opening result in lower temperatures of smoke reaching the exit of the upstream tunnel. This reduction in temperature diminishes buoyancy forces, causing smoke to propagate longitudinally downstream to a greater extent under the influence of horizontal inertial forces, thereby enhancing smoke intrusion.

Lateral natural wind alters the trajectory of smoke flow, diminishing channeling phenomena. As the lateral wind speed increases, the distance between the smoke and the exit of the downstream tunnel becomes greater, leading to a more pronounced reduction in channeling phenomena. Therefore, it may be a measure to reduce the impact of channeling to install additional fans at the outlet of the upstream tunnel to simulate the lateral natural wind.

In this paper, the characteristics of fire smoke diffusion in continuous tunnels under different factors are studied, but only part of the influencing factors are studied, and more comprehensive factors will be improved in the follow-up research.

Acknowledgments

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