Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 7373685, 13 pages
https://doi.org/10.1155/2021/7373685

Research Article

Numerical Simulations on the Extinguishing Effect of Water Mist System with Different Parameters of Longitudinal Ventilation in Curve Tunnel Fire

Zhizhong Liu,[1,2] Chen Chen,[1,2] Mu Liu,[1,2] Song Wang,[3] and Yuzhu Liu[3]

[1]*Hebei Provincial Expressway Yanqing-Chongli Construction Office, Zhangjiakou 075000, China*
[2]*Hebei Provincial Expressway Yanqing-Chongli Management Center, Zhangjiakou 075000, China*
[3]*Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu 610031, China*

Correspondence should be addressed to Yuzhu Liu; liuyuzhu@my.swjtu.edu.cn

Received 2 August 2021; Accepted 5 September 2021; Published 24 September 2021

Academic Editor: Gan Feng

Once a fire occurs in a long curve tunnel, the mixing of hot smoke flow and cold air leads to turbulence due to the curvature's impact. This phenomenon results in a greater thermal pressure difference at the fire source and a substantially greater temperature field than in the straight tunnel. The longitudinal air flowing along the wall loses a lot of velocity in the curve tunnel due to the massive wall friction. Under the same fire extinguishing conditions, the curve tunnel and straight tunnel have different requirements for longitudinal ventilation. Factors such as tunnel curvature, longitudinal ventilation operation time, and ventilation velocity were all evaluated in order to investigate the influence of longitudinal ventilation parameters on the fire extinguishing effect of water mist in the curve tunnel. The fire extinguishing effect of water mist coupling with longitudinal ventilation in the curve tunnel is studied by numerical simulation, and the recommended values of ventilation operation time and ventilation velocity in the curve tunnel with the participation of the water mist system are given. The results show that (1) the fire extinguishing effect of water mist decreases with the increase of curvature under longitudinal ventilation and (2) fire prevention effect is best when water mist and longitudinal ventilation are used in the curved tunnel, and the ventilation velocity should be greater than 2 m/s.

1. Introduction

The mountain tunnels tend to be characterized by crossing deep valleys and high mountains. In order to avoid traversing unfavorable geology and overcome terrains with large elevation differences, more curve tunnels have emerged. The curvature varies from 1/254 to 1/3000. Tunnel fire is the most dangerous disaster during operation period since a large amount of hot and toxic smoke are generated by fire, which seriously affect the safety of passengers and the stability of the lining structure. In addition, the smoke diffusion in the curve tunnel is quite different from that of the straight tunnel due to the interaction of curvature and centrifugal force.

In the curved tunnel, a great number of studies have been performed for the limit and control of smoke. Zhong et al. [1] conducted a full-scale experimental study on the development of flue gas in inclined large curved tunnels of underground natural ventilated spaces under three different fire powers. The experiments measured the vertical smoke temperature rise, the flow characteristics of the fire plume near the fire source, and the variation of maximum smoke temperature during the growth, stabilization, and attenuation phases of the fire. Lou et al. [2] studied the effects of curvature on smoke diffusion by using the software of FDS in a curved tunnel fire, for understanding the correlations between the range of influence and the degree of the tunnel curvature. Li and Xie [3] established a full-scale curve tunnel model based on computational fluid dynamics theory and fire turbulence numerical simulation theory by using the numerical simulation method. The fire and ventilation conditions of the full-scale curve tunnel were studied by CFD simulation software. Caliendo et al. [4] proposed a CFD model simulating the impact of curved bi-directional highway tunnel fire, focusing on the impact of tunnel fire location, tunnel geometry, longitudinal ventilation of jet fans, and existence of the traffic flow on tunnel fire. Although there are a lot of research studies on the curved tunnel, the research on fire extinguishing by water mist in the curved tunnel is still blank. Zhang et al. [5] used FDS 5.5.3 to numerically study the length of the smoke back layer and the critical ventilation velocity of a series of curved subway tunnels with turning radius of 300 to 1000 m at the exothermic rate of 5 and 10 MW. Wang [6] studied the numerical simulation results of critical ventilation speed and smoke movement of fire at different lateral positions of the curved tunnel and also gave the back layer length of three lateral fire positions. Liu [7] described full-scale tests of the water mist fire suppression system under forced desmoking conditions. The smoke exhaust had a strong effect on the water mist to result in a fire that could not be extinguished when the ventilation rate increased to 120.0 m^3/min. This study employed a computer modeling to verify the water mist system in a compartment space and determine how the water mist system could be optimized.

However, only grasping the law of smoke diffusion in curved tunnels is not enough to guide engineering practice. With the deepening of tunnel smoke control, water mist fire extinguishing systems have gradually become one of the auxiliary measures for tunnel fire control. Therefore, a large number of studies have been carried out based on the water mist system. Blanchard et al. [8] focused on the fire in midscale tunnels and conducted experiments and numerical simulations. In their research, water spray was sprayed directly on the fire source to control the fire, opening the longitudinal ventilation system and exploring the law of temperature changes inside the tunnel. The results show that the water mist plays an important role in the absorption of heat, and most of the heat is absorbed by the water droplets. Tang et al. [9] conducted an experimental study on the longitudinal critical velocity. The experimental results show that the critical velocity of the tunnel decreases after the activation of the water-based fire extinguishing system. Li et al. [10] described and analyzed experiments using water mist segments (curtains) to prevent smoke and heat transmission in mesoscale tunnels. The experimental results show that the activation of the water mist section can generally reduce the temperature under the inner ceiling of the reserve. The blocking effect of the water mist section is better when the nozzle is more active and the water pressure is higher. Garo et al. [11] studied the influence of a mist addition as an opposed flow to a small-scale liquid (heptane) pool fire structure, confirming that radiation attenuation cannot be identified as a predominant mechanism of extinguishment. Liang et al. [12] conducted a numerical study on the interaction between lateral ventilation and water mist curtains in large tunnels. The results show that the combination of water curtain and transverse ventilation system can effectively limit fire and smoke, and the environment in the restricted area is suitable for evacuation. Cui and Liu [13] proposed that, without weakening the fire extinguishing effect of water mist, proper mechanical ventilation systems can effectively reduce flue gas concentration, thermal radiation intensity, and total heat flux intensity. It can also increase the concentration of O_2 and reduce CO volume fraction. To some extent, the combined action of mechanical ventilation systems and water mist will help ensure personnel safety in the fire ground. Chen et al. [14] found that when the interval between the mist nozzle and fire source enlarges, the relationship curve between fire suppression time and ventilation velocity shows a 'V' figure.

However, the research object of the above research is mainly straight tunnels. There are less research studies on the coupling of curved tunnels. Excessive air reduces fire extinguishing efficiency, but appropriate ventilation can slightly enhance fire combustion and further strengthen the effect of cooling by water mist. The incomplete combustion of combustibles produces CO and fumes, which form a thick and dense smoke layer. The hot smoke layer is hardly penetrated by finer droplets, but smoke concentration can be decreased by the dilution of air and the complete combustion of fuel. This effect helps water droplets reach the fire. Meanwhile, convective heat transfer and radiation attenuation caused by fresh air play their active roles in decreasing the radiant heat feedback of smoke on combustibles. When the water mist system and ventilation system are used at the same time in the tunnel, a complex situation of water mist, fire, and ventilation coupling is formed, which mainly affects the fire extinguishing. There are many cases in which two kinds of systems are used at the same time and the ventilation system is longitudinal ventilation. The specific engineering results are shown in Table 1 [15, 16], including the Jinjiazhuang Tunnel. Longitudinal ventilation will often have adverse effects on water mist fire extinguishing, which is mainly reflected in two aspects: (1) the longitudinal ventilation system will change the original motion trajectory of the water droplets while removing high temperature and toxic smoke, causing the water droplets to deviate from the fire source, which may cause the water mist with a small particle size to fail to reach the root of the flame, as shown in Figure 1. The fire extinguishing effect is reduced because the mechanical exhaust increases the buoyancy of the fire plume and affects the momentum of the water mist reaching the root of the flame. (2) Longitudinal ventilation in the highway tunnel will bring a lot of fresh air, which will bring sufficient oxygen to the fire source in the tunnel and even play a combustion-supporting effect. This is not good for tunnel fire extinguishing. These adverse effects not only appear in the straight tunnel but also apply to the curve tunnel.

Current research mostly focuses on exploring the influence of longitudinal ventilation in linear highway tunnels on water mist fire extinguishing [17–19]. Therefore, according to the actual size of the Jinjiazhuang Tunnel and the method of FDS numerical simulation, this paper studies the interaction between the longitudinal ventilation and the water mist system, the reasonable opening time, and the design wind speed of the longitudinal ventilation under different curvatures. And, the corresponding suggested values are given. The results can provide references for tunnel designers in the design of tunnel fire control and smoke exhaust.

2. Numerical Simulation

2.1. Introduction of FDS. Fire dynamics simulation software (FDS) is a commonly used fire simulation tool, which can comprehensively consider the various processes of fire smoke flow. FDS can also realize the coupled simulation of two-phase flow, smoke, and particles. The Large Eddy Simulation turbulence model was used in this FDS numerical calculation. The main governing equations of FDS [20] are as follows:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0. \tag{1}$$

Conservation of momentum:

$$\rho\left(\frac{\partial u}{\partial t} + (u \cdot \nabla)u\right) + \nabla p = \rho g + f + \nabla \cdot \tau. \tag{2}$$

Conservation of energy:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h u - \frac{\mathrm{D}p}{\mathrm{D}t} = \cdot q''' - \nabla \cdot q_r + \nabla \cdot k\nabla T + \nabla \cdot \sum_l h_l (\rho D)_l \nabla Y_l. \tag{3}$$

Conservation of species:

$$\frac{\partial}{\partial t}(\rho Y_l) + \nabla \cdot \rho Y_l u = \nabla \cdot (\rho D)_l \nabla Y_l + \cdot m'''. \tag{4}$$

The spray characteristics are defined by a set of parameters, including fluid thermal characteristics, droplet size distribution, and spray characteristics. In the FDS spray model, Lagrange particles are used to represent water droplets. The droplet size distribution is represented by lognormal distribution and Poisson distribution:

$$F(d) = \begin{cases} \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_0^d \frac{1}{\sigma d'} e^{-\left[\ln\left(d'/d_m\right)\right]^2/2\sigma^2 dd'} & (d \le d_m) \\ 1 - e^{\left(-0.693\left(d/d_m\right)^r\right)} & (d_m < d) \end{cases} \tag{5}$$

The mass and energy transfer formula of the vapor phase or droplet is as follows:

$$m_l C_l \frac{\mathrm{d}T_l}{\mathrm{d}t} = \mathrm{Ah}\left(T_g - T_l\right) + \mathrm{Ah}_s\left(T_s - T_l\right) + q_r + \frac{\mathrm{d}m_l}{\mathrm{d}t} h\nu. \tag{6}$$

2.2. Numerical Model. Based on the real size of Jinjiazhuang Tunnel, a numerical model is established, and the curvatures are 1/860, 1/500, and straight. The size of the numerical model is 300 m × 13 m × 8.7 m (length × width × height). The height of the water mist nozzle is 5 m, and the distance between adjacent nozzles is 3 m. The total length of the water mist fire extinguishing area is 50 m. The velocity of the nozzle is 10 m/s, and the flow rate is 15 L/min. The nozzle working pressure is 12 MPa, and the diameter of the water mist droplet is 300 μm. The fire source is an oil basin filled with heptane, the fire source area is 0.36 m^2, the fire size is 30 MW, and the fire source is located 50 m away from the entrance of the tunnel.

The simulated ambient temperature is 20°C, and the boundary conditions of inlet and outlet are set as "open." The inlet boundary condition is changed to "supply" to represent longitudinal ventilation in the tunnel.

The water mist system is activated 90 s after ignition, and the visibility and temperature concentration measurement points are arranged at the height of the human eye (2.0 m from the ground) and the height of the vault. The visibility and temperature are recorded every 1 second. Figure 2 shows the locations of the measuring points discussed in the numerical simulation. In addition, in order to monitor the flow and temperature field, horizontal slices at different heights (medium height $z = 2.0$ m and slightly lower than the ceiling $z = 4.9$ meters) and longitudinal slices at different distances from the fire source (10 m, 20 m, 30 m, 50 m, and 100 m from the fire source) are defined.

Considering the radius of curvature, the speed of longitudinal ventilation, the opening time of longitudinal ventilation, and other factors, 21 working conditions are designed, as shown in Table 2. Calculation condition 1–20 is used to study the effect of water mist fire extinguishing under multifactor coupling. To verify the accuracy of FDS, calculation condition 21 is designed according to the experiment of small-sized tunnel longitudinal smoke exhaust and high-pressure water mist [21].

2.3. Sensitivity Study on the Grid Size. During the FDS fire simulation, the size of the grid determines the accuracy of the simulation results. As the number of grids increases, the calculation results are more accurate, but the calculation time increases. Therefore, the grid size is usually determined by the characteristic fire diameter D^* of the fire source. It is suggested that when the grid size is taken as 1/10 of the characteristic fire diameter, the simulation results are accurate. The D^* calculation formula [22] is as follows:

$$D^* = \left(\frac{Q}{\rho_\infty c_\infty T_\infty \sqrt{g}}\right)^{2/5}. \tag{7}$$

The heat release rate is the key factor directly affecting the fire characteristics. For a 30 MW fire, the value of D^* is about 3.66 m. This means that a mesh size of 0.36 m or less should provide reliable results. To obtain the proper grid sizes, grid sensitivity analyses are carried out as in the previous studies [17]. The grid sizes of 0.2 m, 0.25 m, and 0.5 m are selected in the current work.

Figure 3 shows the temperature distribution of the tunnel longitudinal section near the fire source with different grid sizes. The 0.5 m grid size has a faster temperature rise because the location of the fire source is larger than other

Table 1: Typical engineering application of the water mist fire extinguishing system in the tunnel space.

Application place	Country	Fire extinguishing system	Ventilation system
Hugh L. Carey Tunnel	USA	Water mist	Longitudinal
Gran Sasso National Laboratory Underground Tunnel	Germany	Water mist	Longitudinal
Virgolo Tunnel	Italy	Water mist	Longitudinal
Eurotunnel	France and UK	Water mist	Longitudinal
New Tyne Crossing	UK	Water mist	Longitudinal
Saadiyat Island Service Tunnel	Abu Dhabi	Water mist	Longitudinal

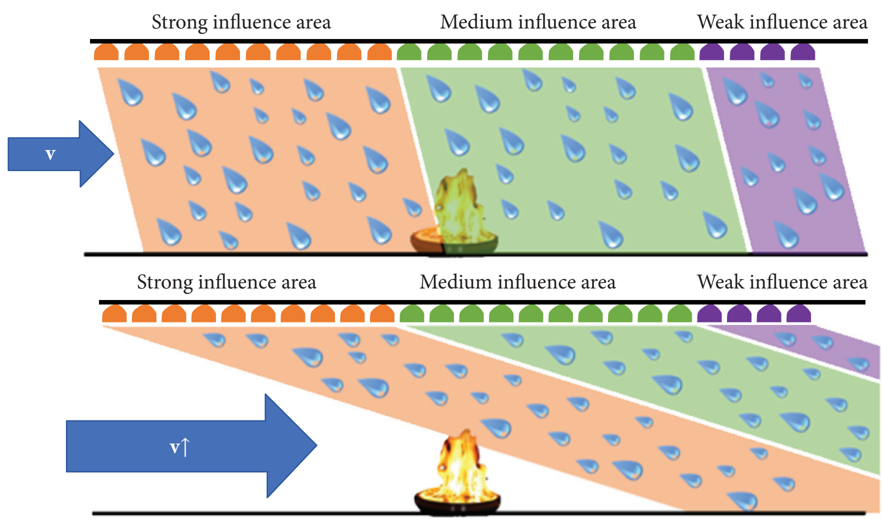


Figure 1: Water mist droplets have long downstream distance at higher longitudinal ventilation.

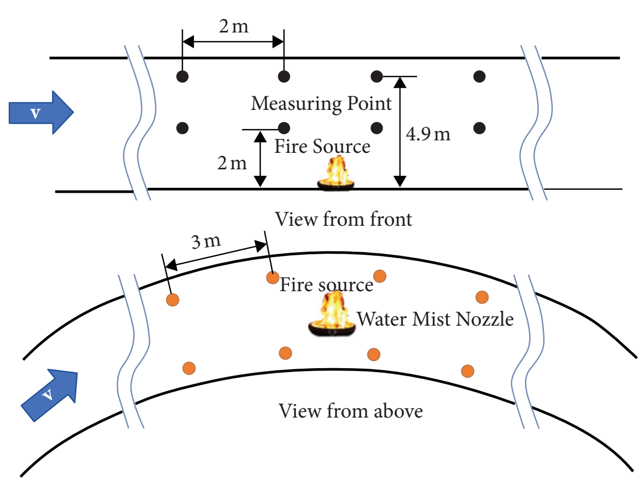


Figure 2: Schematic diagram of the arrangement of fire source, water mist nozzle, and measuring points.

grids. Thicker mesh has thicker layer of smoke, and results of grid sizes of 0.2 m and 0.25 m are nearly the same. Therefore, the grid size used in FDS calculation in this study is 0.25 m.

3. Result and Discussion

3.1. Validation Work. To verify the correctness of the FDS calculation, a small-scale tunnel longitudinal smoke exhaust and high-pressure water mist coupling experimental model of Zhang et al. [21] is selected for numerical simulation. The model size (length × width × height) is 6 m × 1.5 m × 2 m, and a small diesel pool fire (250 mm × 200 mm) is used as the research object. The oil pool is located directly under the water mist nozzle. One of the calculation is selected for verification. Under this calculation condition, the working pressure of the water mist nozzle is 15 MPa. The actual flow rate is 19 L/min, and the droplet diameter is ≤200 μm. The fan is opened to ensure that the longitudinal ventilation wind speed reaches 1 m/s. Both longitudinal ventilation and water mist turn on 90 s after the oil pool is ignited.

Table 2: Simulation scenario.

Calculation condition	Radius of curvature	Fire scale	Opening time of water mist (s)	Longitudinal ventilation speed (m/s)	Opening time of longitudinal ventilation (s)
1	0	30 MW	90	2	-
2					60
3					90
4					120
5	500	30 MW	90	2	-
6					60
7					90
8					120
9	860	30 MW	90	2	-
10					60
11					90
12					120
13	500	30 MW	90	1	90
14				2.5	
15				3	
16				4	
17	860	30 MW	90	1	90
18				2.5	
19				3	
20				4	
21	0	35 kW	90	1	90

Measuring points at a height of 500 mm directly above the fire source and a height of 1500 mm from the ground are set to measure the fire field temperature.

The comparison between FDS calculation results and model test results is shown in Figure 4. The trends of FDS simulation results and the experimental results are in general agreement. The temperature of the measuring point increases continuously before the water mist is turned on. It rises for a short time after the activation of water mist and then decreases. The error is controlled within 15% to meet the error requirements [23]. Therefore, the results obtained by FDS are credible.

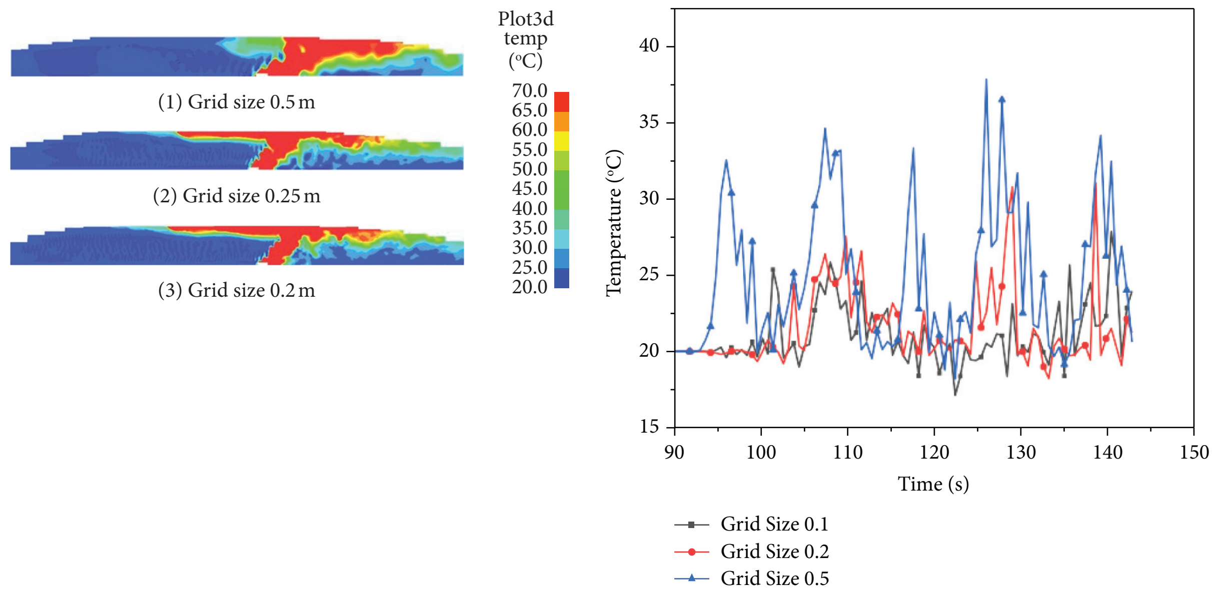
3.2. The Effect of Longitudinal Ventilation on Water Mist System under Different Curvatures. The water mist has a more stable form without mechanical ventilation, which plays a better role in blocking the smoke and reducing the temperature significantly. However, the movement of the droplets will be greatly disturbed with the opening of longitudinal ventilation. The droplets fall on the road at a long downstream distance, reducing the effect of smoke insulation and cooling. Generally speaking, the airflow is more likely to be disturbed at a small particle size under the action of forced ventilation. The disturbance causes the droplets' velocity to be unstable, reducing the momentum of droplets, which has an adverse effect on extinguishing fire.

Figure 5 shows the vault temperature change curve of a tunnel with a curvature of 1/500 and 1/860 under different longitudinal ventilation speeds. With the increase of ventilation speed under different curvatures, the variation trend of temperature is consistent. Under the same curvature, the higher the longitudinal ventilation speed, the lower the temperature in the tunnel. The highest temperature is 261°C at the vault height, and the lowest temperature is 20°C. When the longitudinal ventilation speed is 2 m/s, the high temperature danger zone (the area where the temperature is higher than 60°C at human eye height) near the fire source is the shortest. The upstream of the tunnel is kept at a normal temperature of 20°C, as the longitudinal ventilation speed increases to 3-4 m/s. Within 100 m downstream the fire source, the temperature fluctuates due to the flue gas's disturbance by the convection of cold and hot air. With the increase of the longitudinal ventilation speed, the fluctuation becomes more intense.

The temperature change curve of the tunnel with a curvature of 1/500 at different longitudinal wind speeds at the height of the human eye is shown in Figure 5(b). The temperature in the upstream of the fire source is basically kept within the safety limit and reaches 100°C near the fire source. With the increase of ventilation speed, the disturbance of the smoke flow becomes more severe, and the temperature at the height of the human eye within 50 m downstream of the fire source fluctuates continuously. When the longitudinal ventilation speed is 2 m/s, the high temperature danger zone is the shortest. The temperature fluctuation tends to be stable after 50 m downstream of the fire source, and the temperature only fluctuates between 35–45° after 100 m.

3.3. Operation Time of Ventilation System under Different Curvatures

3.3.1. Temperature Variation under Different Curvatures. The smoke generated in highway tunnel fire has a very high temperature. For the lining, the high temperature will cause the concrete lining structure to burst, which will affect the



(a)

(b)

Figure 3: Grid sensitivity: comparison of temperature contour plots in the vertical midplane for 3 mesh cell sizes for simulation 11. (a) Temperature contour plots in the vertical midplane. (b) Temperature change curve at human eye height under different grid sizes.

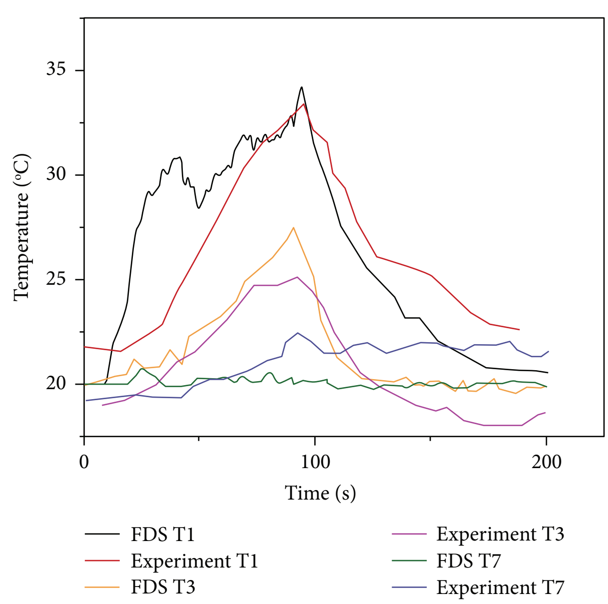


Figure 4: The temperature observed by Zhang et al. vs. the results reproduced by FDS.

safety of the lining structure. For people, the heat radiation in the fire causes burns. Therefore, it is necessary to launch the study of the temperature change at the height of the eye and the height of the vault under the coupling of tunnel fire, water mist, and longitudinal ventilation.

(1) Temperature Variation at Vault Height. The temperature distribution is studied to explore the influence of the coupling of longitudinal ventilation and fine water mist in tunnels with different curvatures. Figure 6 shows the temperature changes of tunnel vaults of various curvatures when longitudinal ventilation is turned on at 60 s, 90 s, and 120 s and without longitudinal ventilation. The flue gas temperature fluctuates greatly near the fire source. As the curvature increases, the resistance and the temperature at the same height increases. After the longitudinal ventilation is turned on in various simulation conditions, the temperature drops significantly, as shown in Figure 6. With the axial flow fan operation time in advance, the cooling time is shortened. Longitudinal ventilation is started in 60 s, 90 s, and 120 s, and the time required for the temperature of the vault above the fire source to stabilize at about 60°C is 150 s, 130 s, and 140 s, respectively.

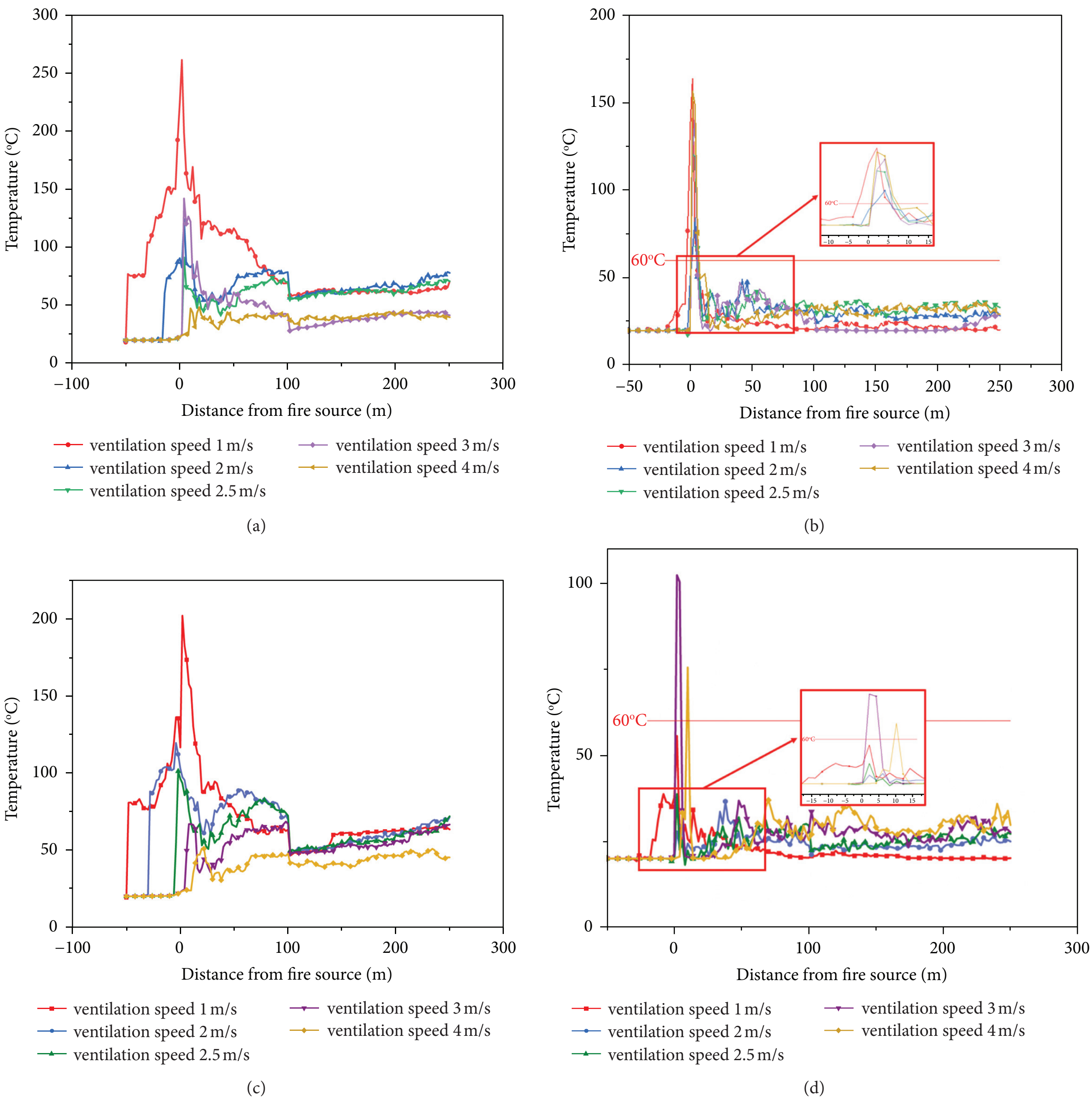


FIGURE 5: Variation of temperature at different heights in curvature 1/500 and 1/860 tunnels under different longitudinal ventilation speeds. (a) Variation of vault temperature in curvature 1/500 tunnel under different longitudinal ventilation speeds and variation of vault temperature in curvature 1/860 tunnel under different longitudinal ventilation speeds. (b) Variation of eye height temperature in curvature 1/500 tunnel under different longitudinal ventilation speeds and variation of eye height temperature in curvature 1/860 tunnel under different longitudinal ventilation speeds.

The cooling effect under the condition of 120 s longitudinal ventilation is better than that the condition without longitudinal ventilation, which shows that turning on the longitudinal ventilation has a significant effect on reducing the temperature in the tunnel. As shown in Figure 6, when the longitudinal ventilation and water mist are turned on at the same time, the temperature in the tunnel is relatively low, basically maintaining below 35°C. Comparing the calculation simulations of different operation times, it is not that the temperature in the tunnel drops faster when the ventilation is opened earlier. The longitudinal temperature distribution in the tunnel is related to the degree of influence of longitudinal ventilation on the water mist. When the longitudinal ventilation is turned on too early, the temperature drop is not obvious due to the downstream distance of water mist droplets. The hot smoke cannot be eliminated in time with the delayed opening of longitudinal ventilation. Since the initial water mist has a higher flow rate and a lower

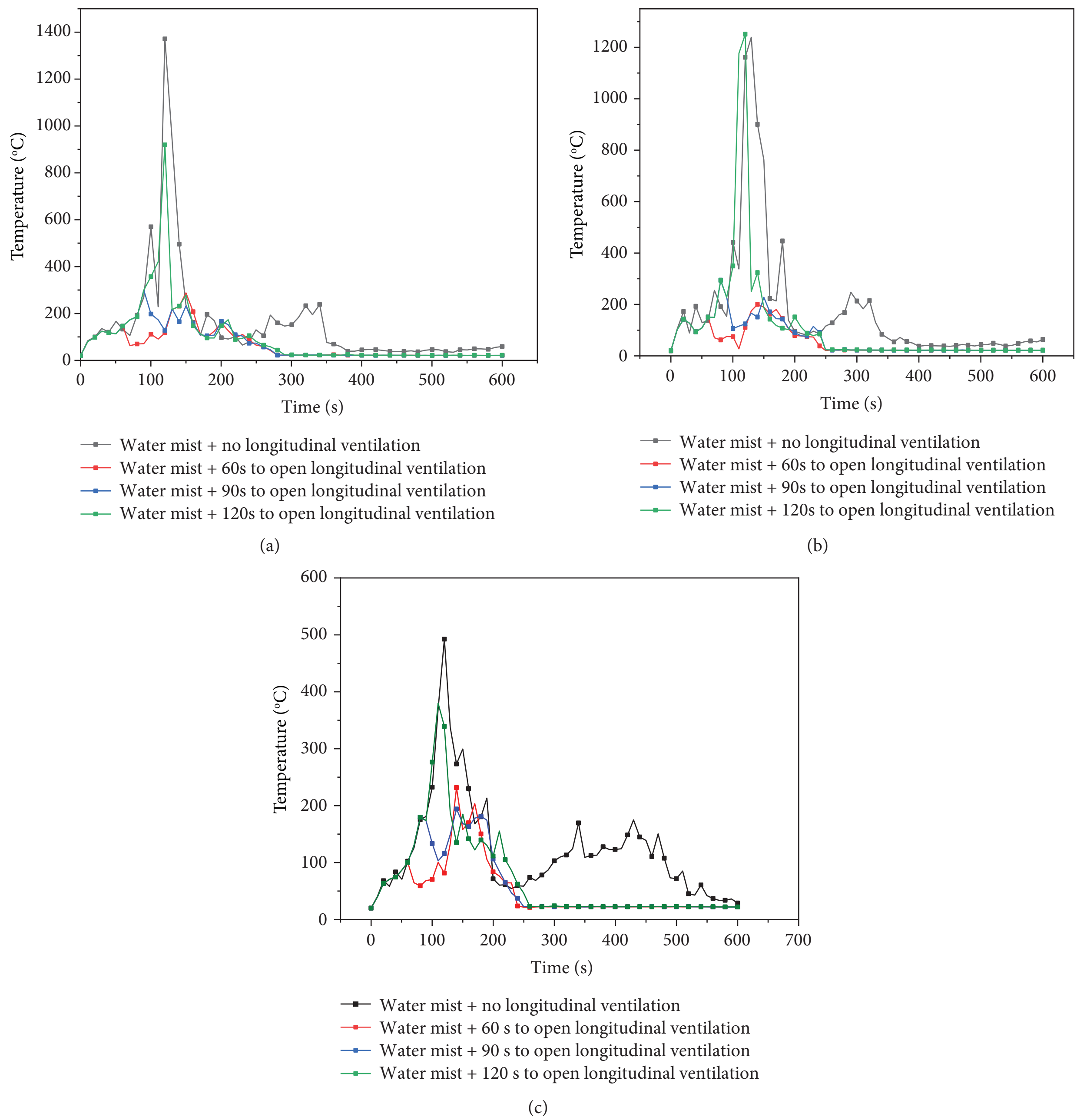
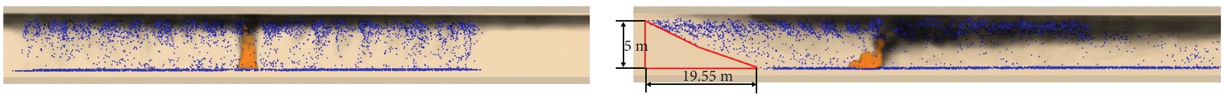


Figure 6: Temperature at vault height under different curvatures. (a) Straight tunnel. (b) Curvature 1/500 tunnel. (c) Curvature 1/860 tunnel.

longitudinal wind speed, the effect of longitudinal ventilation on water mist is very small, so the fire extinguishing effect is obvious, as shown in Figure 7. On the contrary, the longitudinal ventilation allows the smoke flow continuously making the droplets entering the flame zone and reducing the heat radiation of the flue gas.

(2) Temperature Variation at the Height of Human Eyes. The temperature distribution diagram of each tunnel cross section when the curvature is 1/860 is shown in Figure 8. As shown in Figure 8, the high temperature area is mainly concentrated in the range of 100 m downstream of the fire source, and there is obvious temperature stratification. The highest temperature is 55°C in the middle of the tunnel, and the temperature in the area below 2 m is close to normal temperature. The hot flue gas velocity upstream of the fire source is relatively slow on account of the resistance of the longitudinal ventilation. Then, the upstream smoke flows back to the downstream part. In this process, the smoke plume gradually loses its buoyancy and sinks to the lower part of the tunnel, causing the cross-sectional temperature of the downstream part of the fire source to reach about 50°C. The earlier the longitudinal ventilation operates, the faster the temperature decreases in the downstream of the fire source.



(a) (b)

Figure 7: Trajectory of water mist droplets in the tunnel. (a) No longitudinal shift. (b) Downstream shift.

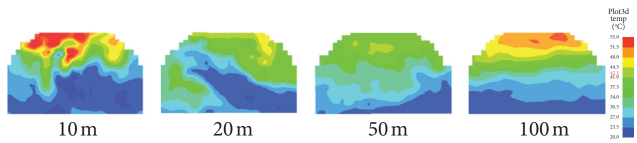


Figure 8: Temperature field change in each cross section of calculation condition 11.

3.3.2. Cooling Effect under Different Curvatures. According to NFPA-15, water spray shall be considered effective for any one of or a combination of the following objectives: (1) extinguishment of fire; (2) control of burning; (3) exposure protection; (4) prevention of fire. Figures 9(a)–9(c) show the change curve of the fire source heat release rate under various simulation conditions. Figure 9(d) shows the time required for fire control under different ventilation operation times.

Through comparative analysis, it is found that, with the advance of fan's starting time, the fire extinguishing time is shortened and the effect is obvious. The starting time of the fan under the straight and curve tunnels has different effects on the time required to extinguish the fire. In the curve tunnel, the fire control time increases with the increase of curvature. In curvature 1/500 tunnel, time required for controlling fire decreases from 220 s to 190 s with the advance opening of longitudinal ventilation of 120 s to 90 s. This is because the wall resistance of the smoke in the tunnel increases with the increase of curvature. The heat release rate of the fire source will increase for a short time after the operation of ventilation in each simulation condition, indicating that the longitudinal ventilation has an accelerating effect on the heat release rate of the oil and fire.

3.4. Velocity of Ventilation System under Different Curvatures. With the massive production of fire smoke, the smoke contains a large amount of toxic and harmful gases and dust, causing the victims to experience the physiological phenomena of poisoning. The spreading high temperature smoke obscures the sight of people and greatly reduces the speed of evacuation. Relevant research shows that the critical conditions of fire risk in the tunnel are as follows:

(1) At a height of 2.0 m that is characteristic of human eyes in the tunnel, the flue gas temperature does not exceed 60°C

(2) At a height of 2.0 m, the visibility of the human eye is less than 10 m

3.4.1. Temperature Variation at the Height of Human Eyes. Figure 10 shows the velocity field at the height of the human eye in the tunnel under different radius of curvature. As shown in Figure 10, there is a small section of flue gas countercurrent upstream of the fire source. The mixing of hot smoke and cold air forms vortex. Due to the viscosity of the fluid and the increased wall friction at the tunnel bend, a large velocity gradient is formed on the wall surface, and the velocity at the center of the tunnel was about 3 m/s. Meanwhile, affected by the hot smoke, the hot and cold air in the tunnel is strongly convective, resulting in uneven velocity distribution within a certain range downstream the fire source. In the downstream of the remote, the velocity near the wall decreased, and the center velocity increased to about 3.5 m/s due to the influence of curvature.

Compared with the straight tunnel, the smoke velocity at the side wall is reduced as a result of the impact of the side wall in the curve tunnel, and the smoke velocity at the center is higher.

Figure 11(a) is a temperature field at the height of the human eyes in the tunnel under different curvatures. The high temperature zone of a straight tunnel is located within 50 m downstream of the fire source, while the high temperature zone of a curve tunnel fire is mostly concentrated within 100 m downstream of the fire source. The temperature on one side of the tunnel bending direction is higher than the other side in the curve tunnel. Affected by tunnel wall resistance, the greater the curvature of the curve tunnel, the higher the temperature.

As shown in Figure 11(b), comparing the temperature distribution at the height of the human eyes in different curvatures, it can be seen that the greater the curvature, the shorter the length of flue gas reflux. The temperature is closer after 100 m downstream of the fire source. The temperature of the tunnel with large curvature is higher than that with small curvature.

3.4.2. Visibility Variation at the Height of Human Eyes. Visibility is inversely proportional to the concentration of carbon particles in a fire scenario. Both CO and soot particles

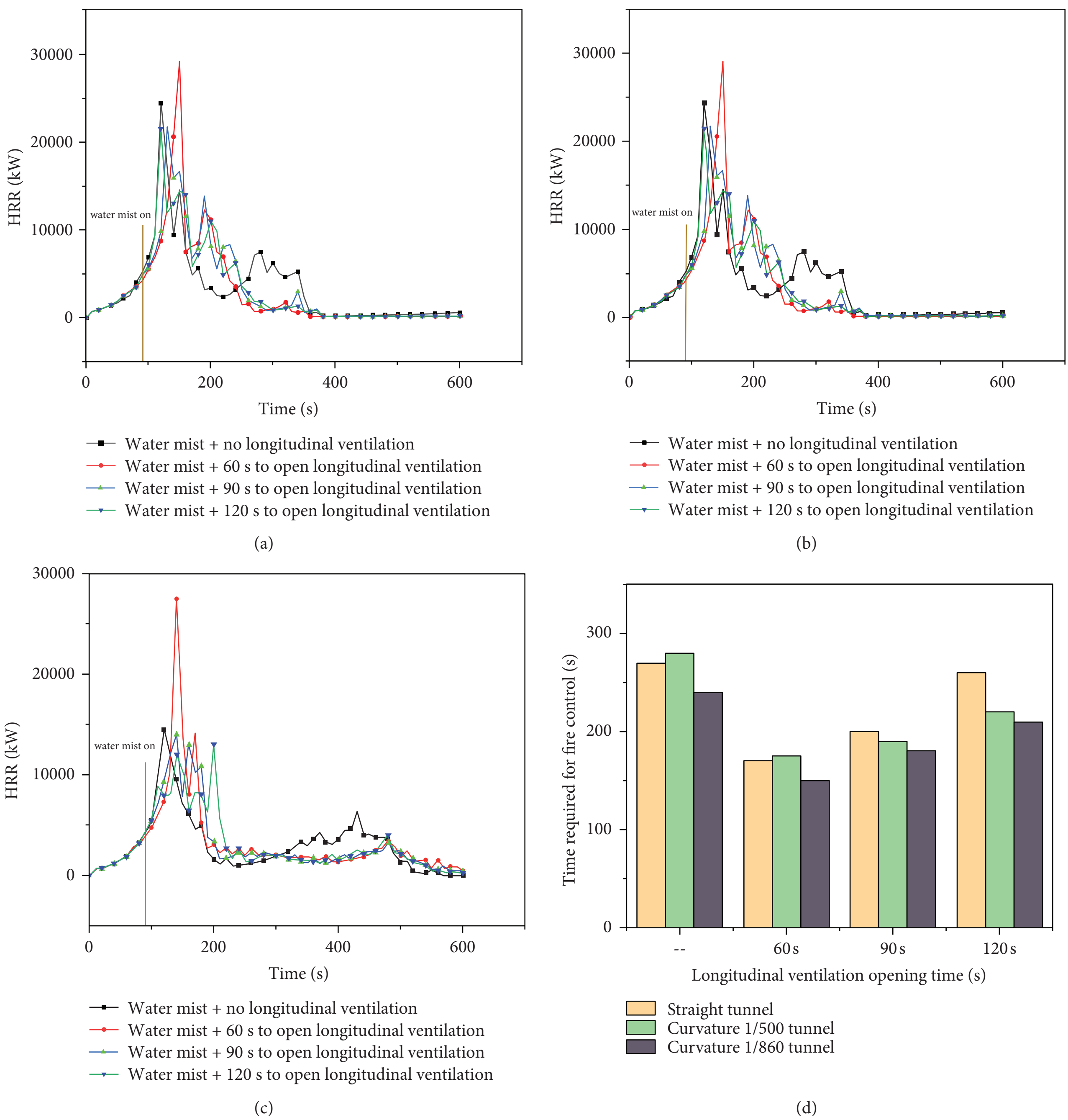


Figure 9: Variation of the heat release rate under different curvatures and time required for controlling fire. (a) Straight tunnel. (b) Curvature 1/500 tunnel. (c) Curvature 1/860 tunnel. (d) Time required for controlling fire.

are produced with incomplete combustion. In the process of flue gas diffusion, the concentration of CO and soot particles will be diluted to a stable degree.

As shown in Figure 12, there is no smoke upstream of the fire source at 200 s, and the visibility is 30 m. The early opening of the longitudinal ventilation can significantly improve the visibility of the fire area and reduce the adverse effect of the water mist on the visibility. Visibility drops to 10 m within 20 m near the fire source, and the greater the curvature is, the lower the visibility is. Due to the stratification of the flue gas in the downstream, soot particles are relatively small, and the visibility is increased to 30 m at a distance of 20 m from the fire source. The variation of visibility at human eye height under different curvatures shows that the greater the curvature, the lower the visibility.

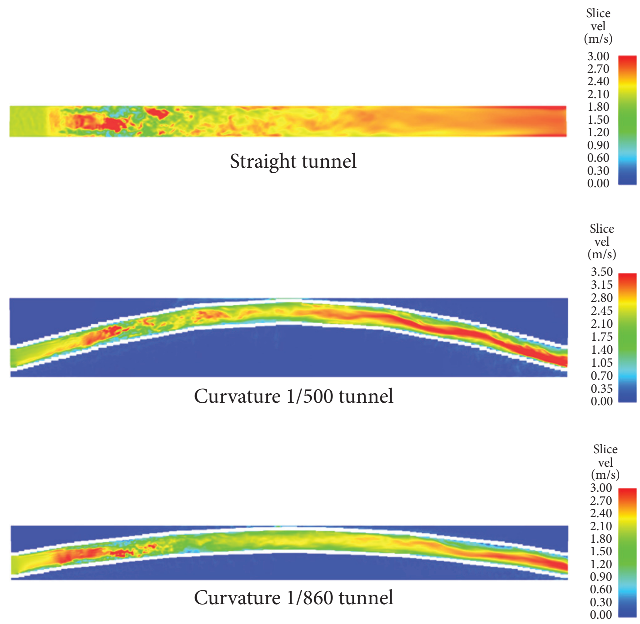


Figure 10: Velocity field in the human eye height plane.

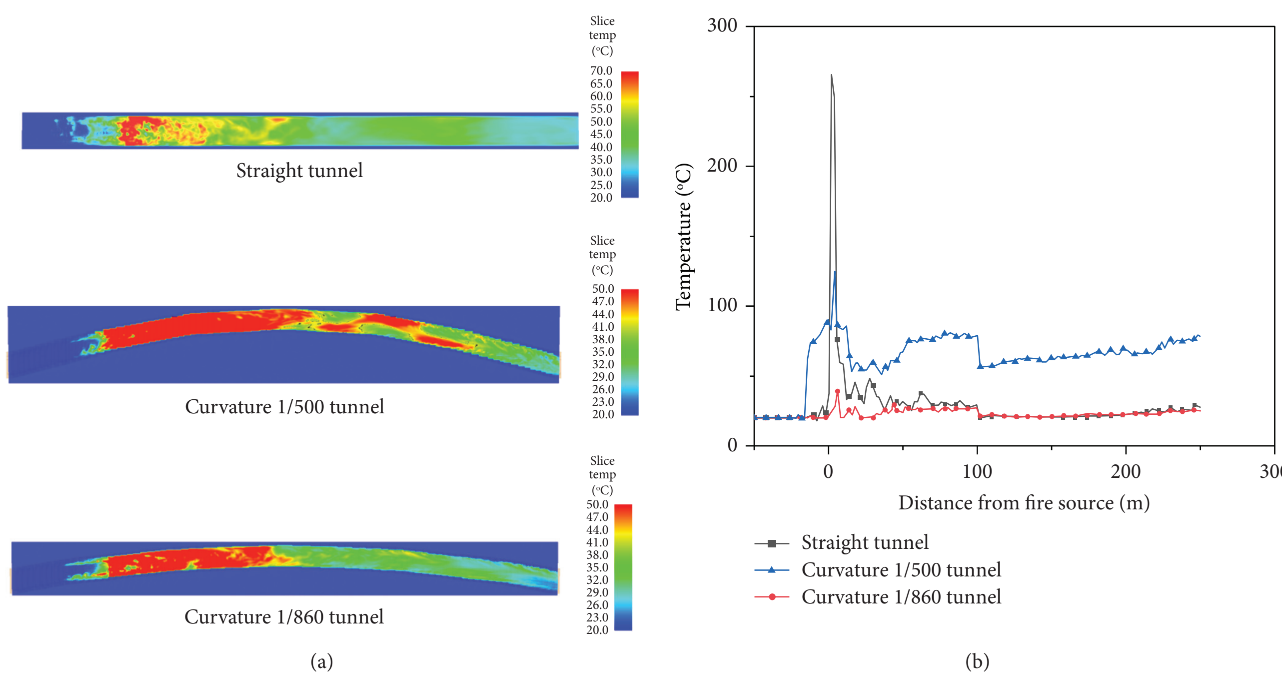


Figure 11: Longitudinal distribution of temperature at eye height. (a) Temperature field at the height of the human eye. (b) Temperature curve at eye height of 2 m/s ventilation speed.

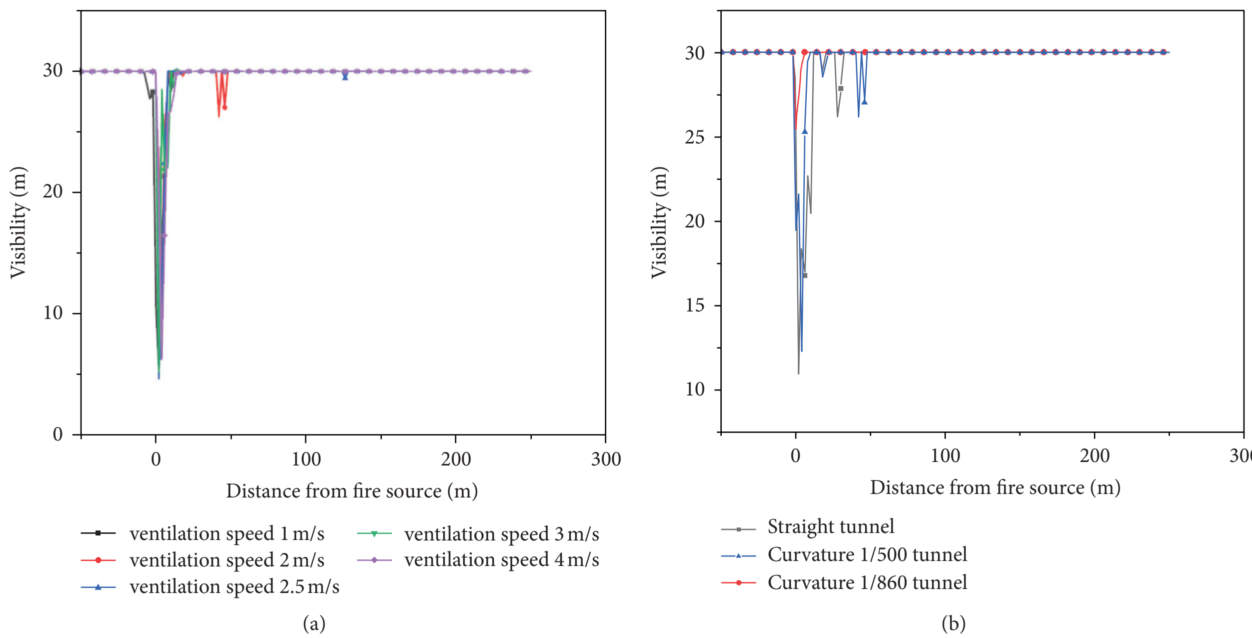


Figure 12: Longitudinal distribution of visibility at eye height. (a) Visibility change curve at human eye height under different longitudinal ventilation speeds. (b) Visibility curve at eye height of 2 m/s ventilation speed.

4. Conclusions

The benefit of fire controlling and cooling by water mist in surroundings of a curved tunnel fire is evident and now well analyzed with longitudinal ventilation based on Jinjiazhuang tunnel. A large number of numerical simulations were carried out considering factors of curvature, operation time of longitudinal ventilation system, and longitudinal ventilation speed. The fire extinguishing effects of water mist coupling longitudinal ventilation under different factors were quantitatively analyzed. The conclusions which can be summarized from the study are as follows:

(1) The simulation result of curvature coupling longitudinal ventilation speed shows that the larger the curvature is, the higher the temperature is and the lower the visibility is, which is not conducive to the safe evacuation of personnel. Under the same curvature, the higher the longitudinal ventilation speed, the lower the temperature in the tunnel. But the high temperature danger zone near the fire source is shorter at ventilation speed of 2 m/s. Therefore, it is suggested that the longitudinal ventilation speed should be 2 m/s when the water mist operates.

(2) Through comparative analysis of curvature coupling longitudinal ventilation operation time, it can be concluded that the larger the curvature, the more the required fire control time. Under the same curvature, it is recommended to open longitudinal ventilation and water mist simultaneously at 90 s.

(3) The simulation results for Jinjiazhuang Tunnel with the curve of 1/860 shows that longitudinal ventilation recommended value should be more than 2 m/s for smoke cooling and people evacuation. And, it is suggested that longitudinal ventilation and water mist system operate at the same time in case of fire.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was financially supported by a grant from the Hebei Provincial Expressway Yan Chong Construction Office (Grant no. YC-201903).

References

[1] M. Zhong, C. Shi, L. He, J. Shi, C. Liu, and X. Tian, "Smoke development in full-scale sloped long and large curved tunnel fires under natural ventilation," *Applied Thermal Engineering*, vol. 108, pp. 857–865, 2016.

[2] B. Lou, Q. Rifu, E. Hu, Q. Jiyun, and H. Zhenwen, "Influence of tunnel curvature on smoke spread in a tunnel fire," *Journal of the Chinese Institute of Engineers*, vol. 43, no. 4, pp. 386–396, 2020.

[3] T. Li and W. Xie, "Numerical simulation study on impact of slope on smoke temperature distribution and smoke spread pattern in curve tunnel fires," *AIP Conference Proceedings*, vol. 1834, pp. 1–11, Article ID 040036, 2017.

[4] C. Caliendo, P. Ciambelli, M. L. De Guglielmo, M. G. Meo, and P. Russo, "Simulation of fire scenarios due to different vehicle types with and without traffic in a bi-directional road

tunnel," *Tunnelling and Underground Space Technology*, vol. 37, pp. 22–36, 2013.

[5] S. Zhang, H. Yang, Y. Yao et al., "Numerical investigation of back-layering length and critical velocity in curved subway tunnels with different turning radius," *Fire Technology*, vol. 53, no. 5, pp. 1765–1793, 2017.

[6] F. Wang, *Research on Key Parameters of Operating Ventilation in Curved Road Tunnels*, Doctor Degree Dissertation, Southwest Jiaotong University, Sichuan, China, 2010.

[7] W.-Y. Liu, C.-H. Chen, Y.-L. Shu, W.-T. Chen, and C.-M. Shu, "Fire suppression performance of water mist under diverse desmoking and ventilation conditions," *Process Safety and Environmental Protection*, vol. 133, pp. 230–242, 2020.

[8] E. Blanchard, P. Boulet, P. Fromy et al., "Experimental and numerical study of the interaction between water mist and fire in an intermediate test tunnel," *Fire Technology*, vol. 50, no. 3, pp. 565–587, 2014.

[9] F. Tang, F. Z. Mei, Q. Wang, Z. He, C. G. Fan, and C. F. Tao, "Maximum temperature beneath the ceiling in tunnel fires with combination of ceiling mechanical smoke extraction and longitudinal ventilation," *Tunnelling and Underground Space Technology*, vol. 68, pp. 231–237, 2017b.

[10] Q. Li, Z. Tang, Z. Fang, J. Yuan, and J. Wang, "Experimental study of the effectiveness of a water mist segment system in blocking fire-induced smoke and heat in mid-scale tunnel tests," *Tunnelling and Underground Space Technology*, vol. 88, pp. 237–249, 2019.

[11] J. P. Garo, J. P. Vantelon, D. Lemonnier, Effect on radiant heat transfer at the surface of a pool fire interacting with a water mist," *Journal of Heat Transfer*, vol. 133, pp. 1–9, Article ID 023503, 2010.

[12] Q. Liang, Y. Li, J. Li, H. Xu, and K. Li, "Numerical studies on the smoke control by water mist screens with transverse ventilation in tunnel fires," *Tunnelling and Underground Space Technology*, vol. 64, pp. 177–183, 2017.

[13] Y. Cui and J. Liu, "Research progress of water mist fire extinguishing technology and its application in battery fires," *Process Safety and Environmental Protection*, vol. 149, pp. 559–574, 2021.

[14] L. Chen, W. Zhu, X. Cai, L. Pan, and G. Liao, "Experimental study of water mist fire suppression in tunnels under longitudinal ventilation," *Building and Environment*, vol. 44, no. 3, pp. 446–455, 2009.

[15] W. Zhu, *Simulative Studies on Water Mist Fire Suppression under Longitudinal Ventilation in Long and Narrow Spaces*, University of Science and Technology of China, Hefei, China, 2006.

[16] Fogtec GMbH&Co.Kg, "Tunnel protection with water mist," http://www.fotec.com.

[17] J. Sun, Z. Fang, T. Beji, and B. Merci, "Interpretation of flow fields induced by water spray systems in reduced-scale tunnel fire experiments by means of CFD simulations," *Tunnelling and Underground Space Technology*, vol. 81, pp. 94–102, 2018.

[18] T. Deng, S. Norris, and R. N. Sharma, "Numerical investigation on the stability of tunnel smoke stratification under the effect of water spray and longitudinal ventilation," *Tunnelling and Underground Space Technology*, vol. 112, Article ID 103901, 2021.

[19] Y. F. Li and W. K. Chow, "Study of water droplet behavior in hot air layer in fire extinguishment," *Fire Technology*, vol. 44, no. 4, pp. 351–381, 2008.

[20] K. McGrattan, S. Hostikka, J. Floyd et al., *Fire Dynamics Simulator (Version 5)-Technical Reference Guide*, NIST Special Publication 1018-5, National Institute of Standards and Technology, Gaithersburg, MD, 2010.

[21] P. H. Zhang, F. Rui, W.-b. Xu, and X. L. Tian, "Suppression on the tunnel fire by coupling the longitudinal smoke discharge and high pressure water mist," *Journal of Northeastern University*, vol. 34, no. 5, pp. 719–722, 2013.

[22] D. Drysdale, *An Introduction to Fire Dynamics*, pp. 132–138, John Wiley & Sons, Unitied Kingdom, 2011.

[23] S. L. Hu, *Numerical Simulation Study on Curve Tunnel Fire Ventilation*, Southwest Jiaotong University, Chengdu, Sichuan, China, 2010, in Chinese.