Experiment Research on Smoke Temperature Properties Lower Ceiling along Tunnel at Different Longitudinal Ventilation Velocities and Tunnel Slopes

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ABSTRACT: To investigate smoke temperature properties lower tunnel ceiling by longitudinal ventilation velocities and different tunnel slopes when fire occurred in a tunnel, a series of fire tests were conducted in a reduced scaled model tunnel. The model tunnel was 52.5m length, and it had a circular cross-section with an inner diameter of 1.1m. A methanol pool was employed as a fire source. Seven tunnel slopes and four longitudinal ventilation velocities were used to simulate different fire scenarios. The smoke temperatures lower the tunnel ceiling were measured and analyzed. The variation laws of smoke temperature lower the tunnel ceiling were gained, such as the temperature at different distance from the fire source varying with time and with longitudinal distance, the maximum smoke temperature above the fire source. The results show that negative slope has bigger effect on smoke temperature under the same ventilation velocity, and the effect is more as the negative gradient increases. In the same slope tunnel, smoke temperature gradually diminishes as ventilation velocity increases. When the longitudinal ventilation velocity is 1.34 m/s, the smoke temperature of the upstream section of fire source is tendency to normal temperature.
KEYWORDS: model tunnel; fire tests; smoke temperature

INTRODUCTION

Tunnel fire cases have shown that the tunnel ceiling near fire source is continuously roasted by high temperature smoke, which may deteriorate the mechanical properties of lining materials and affect the tunnel structure safety. For example, in the Channel Tunnel fire (Kirkland, 2002), the temperature of fire source was about 1000 , approximately 480m of reinforced concrete was under the influence, damaged range was up to 46m. And in the most seriously damaged section, the thickness of lining was reduced to 40mm from the original 450mm. Therefore, the study on the smoke temperature properties lower ceiling along tunnel has important guiding significance for the fire resistance of tunnel structure and the design of fire protection measures.

Some scholars had carried out correlative study on the smoke temperature properties lower ceiling along tunnel (Hu, Huo, &Peng, 2008; Wang, Jiang, &Zhu, 2009). However, it was hardly any consideration the two factors of tunnel slope and ventilation velocity in these literatures. To investigate smoke temperature properties lower tunnel ceiling by longitudinal ventilation velocities and different tunnel slopes when fire occurs in a tunnel, a series of fire tests were conducted in a reduced scaled model tunnel.

FIRE MODEL TEST SYSTEM

Model Tunnel Design

The reduced scaled model tunnel was made by steel plates according to Froude similarity theory (Quintiere, 1989), with the ratio of 1:9 close to the actual shape of ShiZiYang tunnel section, as shown in FIG.1. In the model test, the change of tunnel slope was by adjusting the height of side A or side B. Positive slope denoted the right opening B higher than the left opening A, and vice versa. The longitudinal ventilation was from A to B. The test velocity was provided by the axial fan installed in the side A. The velocity could be adjusted within 7 m/s scope by the frequency modulator.

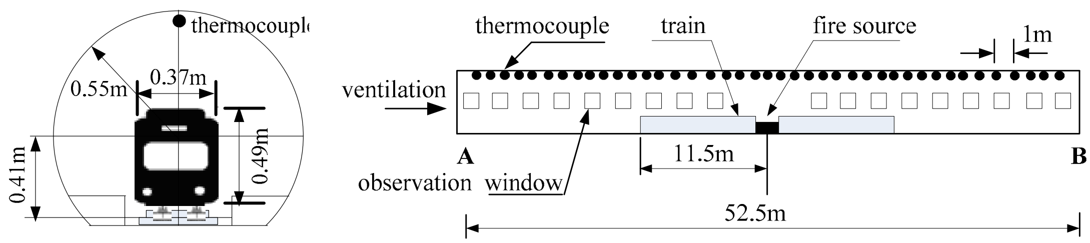


FIG.1. Dimension and ichnography of model tunnel

Measurement system

There were 49 temperature measuring points set in the model tunnel. K-type thermocouples were used as temperature sensor, and fixed at 1 m intervals below the ceiling along the tunnel, as shown in FIG.1. The multichannel temperature gathering meter was adopted to carry on the data gathering, which was capable of completing the collection, upload and memory of all parameters in 5s. The ambient temperature was measured by the ordinary thermometer.

Fire scenes and test series

In view of the fact that the new passenger trains were generally manufactured by inflammable or flame retardant materials, the fire heat release rate of passenger train was assumed to be 15MW in this paper. The experiment selected the methanol as the fuel, and changed fire heat release rate by controlling the area of methanol pool. According to the Froude principle of similitude, the fire heat release rate of 63kW in model test was corresponding to 15MW in entity tunnel, the area of fuel pond was approximately 0.14 m^2. The longitudinal ventilation velocities of 0.34m/s, 0.67m/s, 1.0m/s and 1.34m/s in model test respectively correspond to 1.0m/s, 2.0m/s, 3.0m/s and 4.0m/s in the entity tunnel. And the fire source was 0.17m high in model, which corresponded to the height of 1.8m in entity tunnel. The test series of model tunnel were shown in table 1.

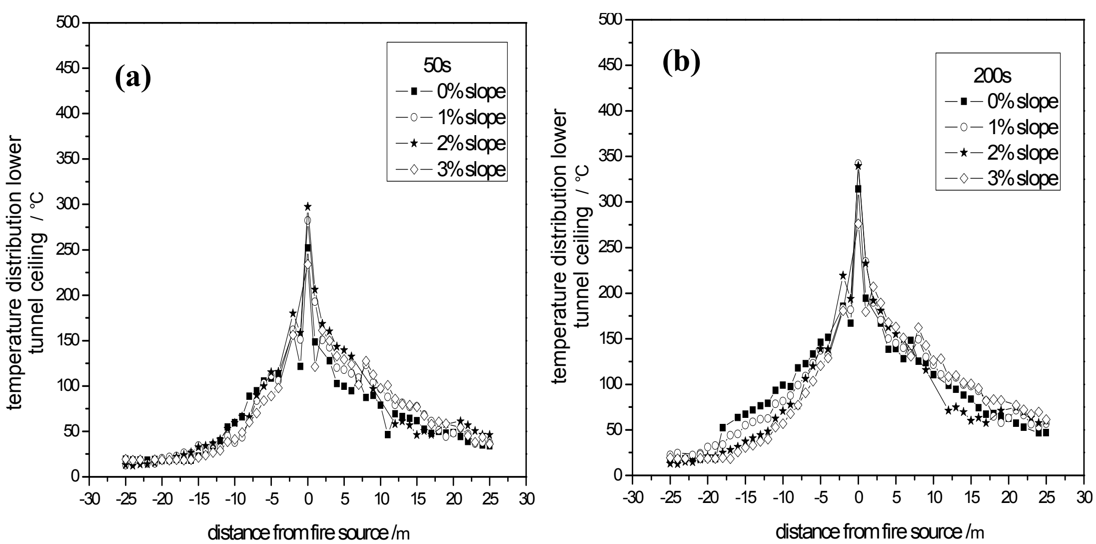
Table1. Model Test Series

Fire Case	Slope (%)	velocity (m/s)	Fire Case	Slope (%)	velocity (m/s)	Fire Case	Slope (%)	velocity (m/s)
1	-3	0.34	11	-1	1	21	2	0.34
2	-3	0.67	12	-1	1.34	22	2	0.67
3	-3	1	13	0	0.34	23	2	1
4	-3	1.34	14	0	0.67	24	2	1.34
5	-2	0.34	15	0	1	25	3	0.34
6	-2	0.67	16	0	1.34	26	3	0.67
7	-2	1	17	1	0.34	27	3	1
8	-2	1.34	18	1	0.67	28	3	1.34
9	-1	0.34	19	1	1	29	0	0
10	-1	0.67	20	1	1.34			

MODEL TEST RESULTS AND ANALYSIS

Smoke Temperature Properties Lower Ceiling along Tunnel without Ventilation

Under the condition of no forced ventilation, the smoke temperature lower ceiling along could be seen in FIG.2. The variation laws obtained from FIG.2 were as follows.



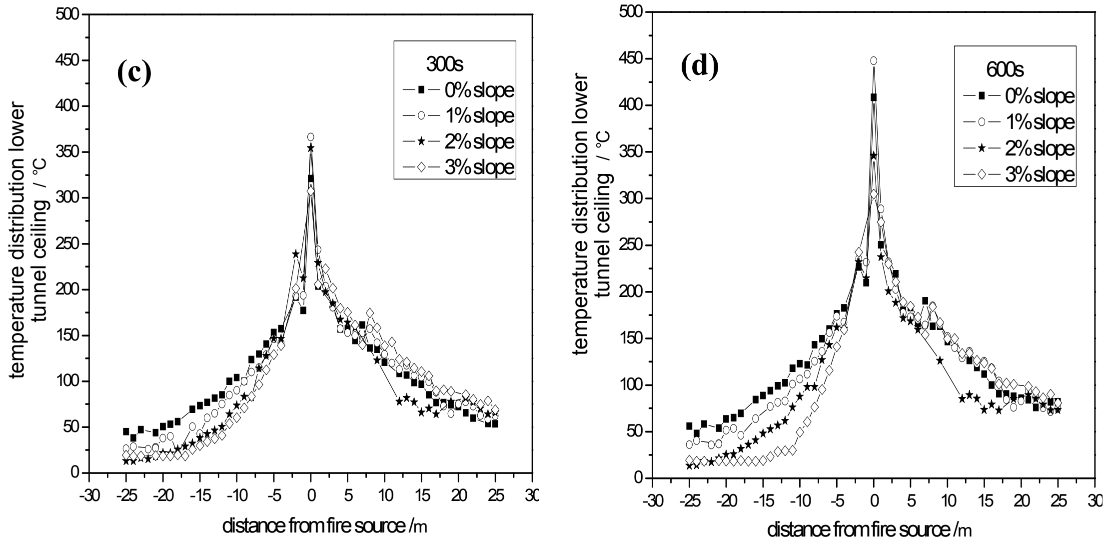


FIG.2. Smoke temperature lower ceiling along tunnel without ventilation

(1) Under the situation of no slope, the longitudinal distribution of smoke temperature lower tunnel ceiling was almost bilateral symmetry of the fire source. The law of temperature change in the point, the same distance upstream or downstream away from fire source, was basically same. When in the slope tunnel, the smoke temperature lower the ceiling at the upstream of fire source was higher than that of the point which was the same distance from fire source in the downstream direction. The distribution of smoke temperature was dissymmetrical along both sides of fire source, and the bigger the slope was, the more obvious the dissymmetry was, which indicated that the slope had certain influence on smoke flow, and leaded to the dissymmetrical variation of smoke temperature lower the ceiling on both sides of fire source.

(2) The temperature at the point of same distance increased along with time continually. In fire development stage, the smoke temperature lower ceiling increased rapidly, the change rate relative to time was bigger. While in fire stable stage, the change rate relative to time was smaller. The smoke temperature decreased along with the increase of distance at the same time, and the temperature decreased along with the increase of slope at the same time and the same distance.

(3) When the smoke temperature of fire source reached the highest value, the other points also reached their maximum temperature. And with the lapse of time, the high temperature smoke was cooled by the building enclosure in the spread process, the temperature declined gradually along the way. The decline gradient of temperature at fire source was bigger than that in the downstream area, and the decline gradient of temperature had gradual reduced tendency along with far away from fire source.

Smoke Temperature Properties Lower Ceiling along Tunnel with Forced Ventilation

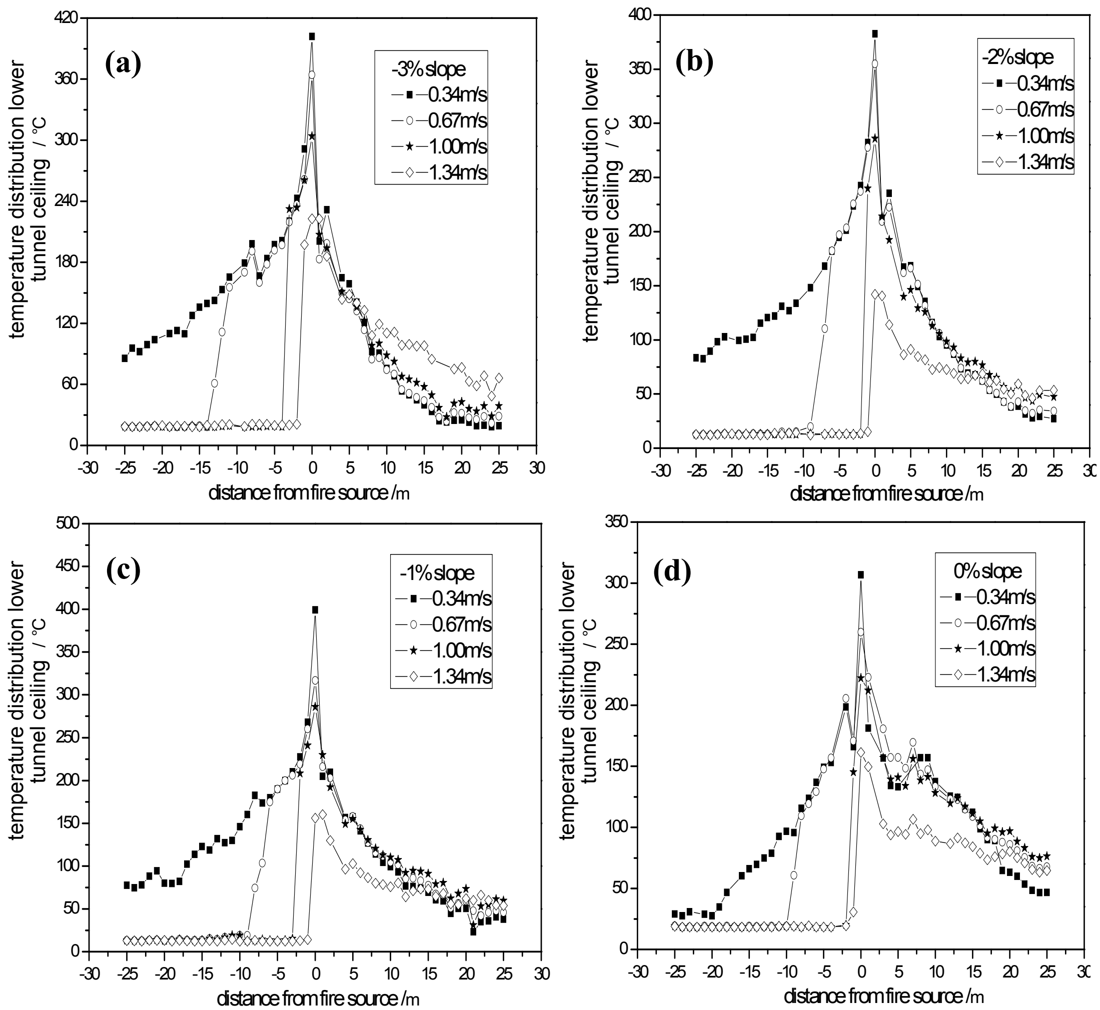
Under the forced longitudinal ventilation condition, the variation laws of smoke temperature lower the tunnel ceiling with the distance away from the fire source was shown in FIG.3. It could be seen from FIG.3:

(1) With the distance far away from the fire source, the smoke temperature lower the ceiling presented the decline tendency generally.

(2) In the same slope tunnel, smoke temperature near fire source gradually diminished as ventilation velocity increases. However, the smoke temperature lower

tunnel ceiling became more equal. When the longitudinal ventilation velocity was 1.34m/s, the smoke temperature of the upstream section of fire source tended to normal temperature. This indicated the back layering was in good control and the upstream area of fire source hardly affected by high temperature smoke. Meanwhile, the damage of high temperature smoke to tunnel lining structure was reduced. An advantageous environment could be provided for passenger evacuation and fire fighter fighting.

(3) Under the identical ventilation velocity condition, with slope change from -3% to +3%, the smoke temperature lower ceiling at downstream point increased gradually with the same distance away from fire source. Moreover, the smoke temperature gradually declined at the upstream point with the same distance away from the fire source. This indicated that the slope had certain influence on the smoke temperature lower tunnel ceiling, and the influence of negative slope was larger than that of positive slope.



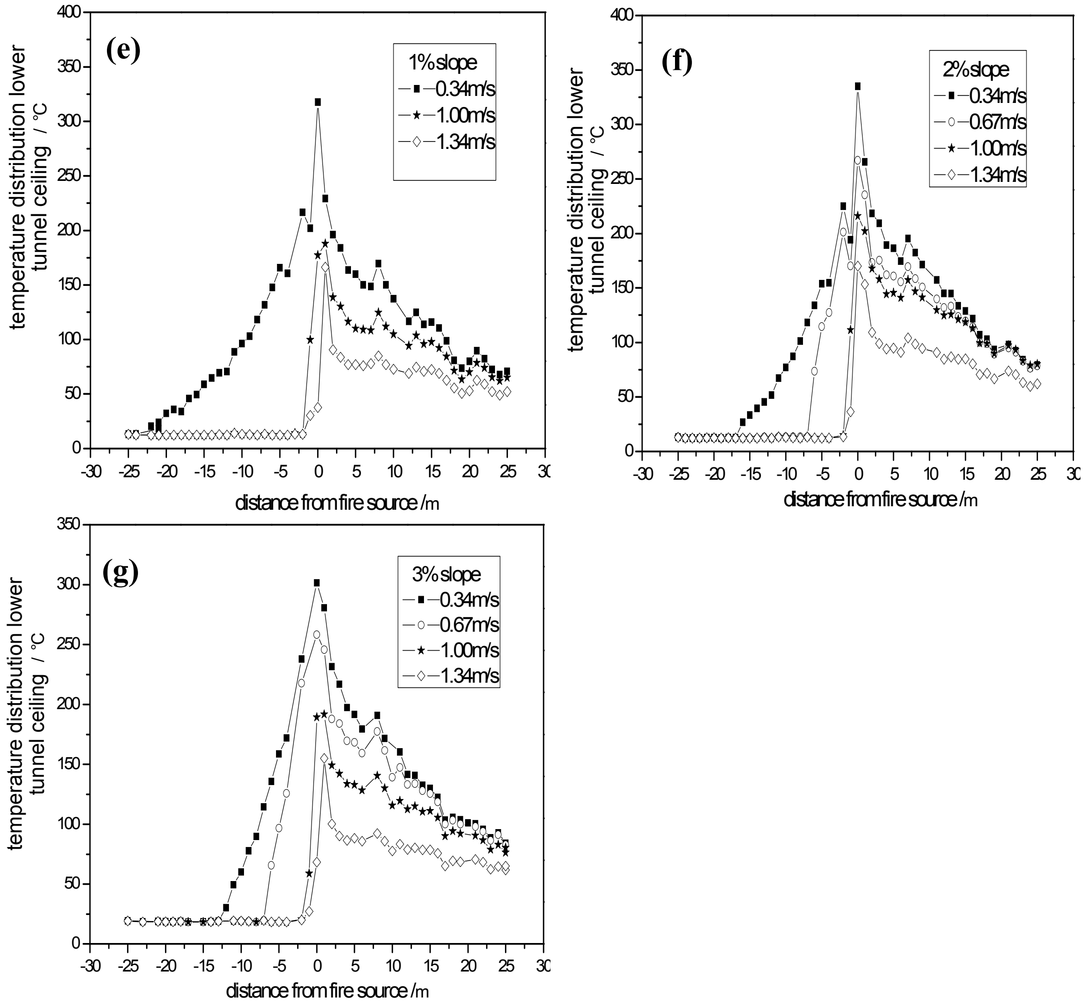


FIG.3. Smoke temperature lower ceiling along tunnel with forced ventilation

Maximum smoke temperature lower tunnel ceiling above fire source

The maximum smoke temperatures above the fire source at different slopes and different ventilation velocities were shown in Table 2 and FIG.4.

Table 2. Model Test Data

Fire Case	Maximum Temperature(℃)	Fire Case	Maximum Temperature(℃)	Fire Case	Maximum Temperature(℃)
1	402	11	286.14	21	335.1
2	364.25	12	160.14	22	267.12
3	304	13	306.72	23	202.22
4	222.67	14	259.84	24	169.94
5	384.25	15	222.22	25	301.38
6	345.75	16	161.26	26	258.17
7	285.88	17	317.71	27	191.91

8	141.99	18	230	28	155.02
9	399.11	19	188		
10	316.91	20	166.28		

(1) Under the condition of different slopes, with the slope change from -3% to +3%, the maximum smoke temperature above fire source presented decline trend at the identical longitudinal ventilation velocity. This was because the function direction of the fire wind pressure was opposite to the function direction of the longitudinal ventilation wind pressure when the slope was negative, and the fire wind pressure was flow resistance. Under the combined action of the negative fire wind pressure and longitudinal ventilation, the smoke would cumulate lower the ceiling to form smoke layer with certain thickness, which caused the smoke to plume immerse in the hot smoke and to lead to the maximum temperature of the ceiling jet go up. While in the positive slope, the function direction of the fire wind pressure was the same as that of the longitudinal ventilation wind pressure, which accelerated the smoke flowing and lessened the heat transfer time of high temperature to tunnel ceiling. However, with ventilation velocity increasing, the influence of slope to the maximum smoke temperature lower the ceiling was gradually wearing off.

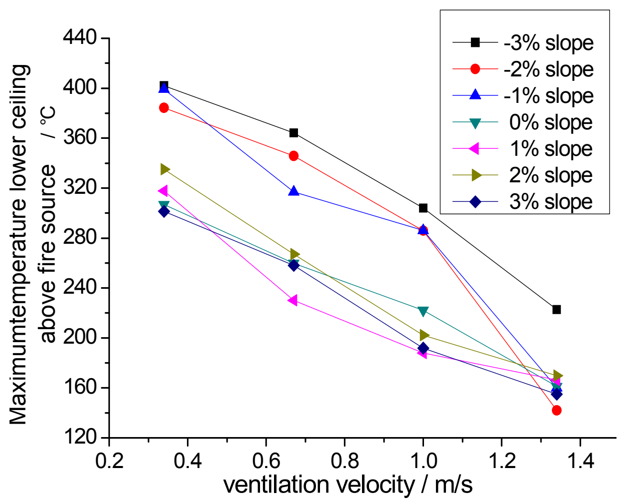


FIG.4. Maximum smoke temperature above the fire source at different tunnel slopes and ventilation velocities

(2) Under the identical slope condition, the maximum smoke temperature lower the ceiling above fire source was declining with the increase of ventilation velocity, and the larger of the ventilation velocity was, the more obvious of the decline of the maximum temperature. It was because the residence time of high smoke temperature lower the ceiling above fire source was reduced by the ventilation velocity increasing. More quantity of heat was taken away from the tunnel at unit time. So the decrease rate of the maximum smoke temperature would speed up with the ventilation velocity increasing.

CONCLUSIONS

(1) The influence of the ventilation velocity and tunnel slope to the distribution of smoke temperature field below the vault is obvious.

(2) Under the situation of no slope and no ventilation, the smoke temperature lower tunnel ceiling is almost bilateral symmetry of the fire source. Yet in slope tunnel without ventilation, the distribution of smoke temperature is dissymmetrical along both sides of fire source, and the bigger the slope is, the more obvious the dissymmetry is. It shows the slope has certain influence on smoke flow and results in the dissymmetrical distribution of smoke temperature on both sides of fire source.

(3) Under the identical ventilation velocity condition, with the slope change from -3% to +3%, test results show that the slope has certain influence on the smoke temperature lower tunnel ceiling, and the influence in negative slope is larger than that in positive slope. When in the condition of identical slope, with ventilation velocity increasing, the smoke temperature near fire source gets less and the smoke temperature distribution becomes more equal. When the ventilation velocity reaches 1.34m/s, the back layering is in good control and an advantageous environment for evacuation and fire fighting can be provided.

(4) The maximum smoke temperature above fire source, with the slope change from -3% to +3%, shows gradual decline trend. Under the identical slope condition, the maximum smoke temperature will decrease as the increase of ventilation velocity. The results show that negative gradient has bigger effect on smoke temperature under the same ventilation velocity, and the effect is more as the negative gradient increases. And the slope influence will gradually wear off with ventilation velocity increasing.

(5) The thermal conductivity between steel plate of tunnel model and concrete in actual tunnel has certain difference, which may has trifle influence on the experiment results. However, the smoke temperature properties lower ceiling along tunnel at different longitudinal ventilation velocities and tunnel gradients still be presented well.

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Numerical Simulation of Smoke Flow Controlling in Railway Shield Tunnel

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ABSTRACT: According to the position of burned train and the location of fire, the numerical simulation of smoke flow controlling was carried out in railway shield tunnel when a train caught fire to stop in the slope section being -3%. Tunnel fans fixed at the rear ingress are immediately to supply fresh air along tunnel, and the fans at the front exit to exhaust smoke. So there exists a great volume of wind along to take smoke outside the tunnel. Large eddy simulation was employed to simulate the smoke temperature, visibility and carbon monoxide concentration distribution in tunnel, at ventilation velocity of 1m/s, 2m/s, 3m/s and 4m/s, respectively. The results show that emergency ventilation policy, 3m/s, can effectively ensure passengers safe evacuation facing with fresh air, and the high temperature smoke under the ceiling do not damage tunnel lining structure. So the emergency ventilation policy is right and the evacuation plan is correct.
KEYWORDS: railway shield tunnel; train fire; smoke flow controlling; numerical simulation

INTRODUCTION

Tunnel fires have obtained special attention in recent years due to several catastrophic fires (Wu and Bakar, 2000; Modic, 2003; Suzuki et al., 2004; Gao et al., 2004; Hwang and Edwards,2005). In China, the tunnel transportation is developing quickly with the increment of the high-speed railway mileage. Extra-long railway tunnels appear continuously. For examples, TaiHangShan tunnel is 27839m long, DaBieShan tunnel is 13526m and XiaPu tunnel is 13099m. For the raise of train operating density and running speed, the possibility of train fire occurrence in extra-long railway tunnels is increasing. If there is no reasonable emergency ventilation design, the train fire may cause tremendous economic losses and social impact.

ShiZiYang railway shield tunnel, the 10800m length, is the first underwater extra-long railway tunnel. Maximum longitudinal slope is ±3%. There are 25 cross channels between double tubes, the distance between which in the longitudinal direction is 500m. Internal diameter of tube is 9.8m and transverse area about 65m^2. Rescue aisle of 2.1m width and 0.7m height is designed in longitudinal direction of tunnel. And the planned air velocity in fire accident is 3.0 m/s. The train CRH1 is 213m long, 3.3m wide and 4.0m high.

In this paper, the train caught fire stopping in ShiZiYang railway shield tunnel was taken as the fire scene. Numerical simulation method was adopted to analyze the longitudinal distribution of smoke temperature, visibility and carbon monoxide(CO), and hereby to evaluate the validity of emergency ventilation design.

CRITERIONS ON VALIDITY OF SMOKE FLOW CONTROL

The validity criterion of ventilation and smoke exhaust system in tunnel is that smoke flow control policy should satisfy passenger safe evacuation and decrease damage to tunnel lining structure as possible.

Passengers Fire Tolerance Degree

Passengers are threatened by smoke, temperature, poison gas and other risk factors during the evacuation. In this paper, the critical value for passengers to tolerate temperature, visibility, smoke layer height, poison gas were summarized in Table 1.

Table 1. Passengers Tolerance Degree in Fire Engineering

Smoke risk factors	*Temperature*	*CO*	*Visibility*	*Hot smoke layer height*
The critical value	< 60℃	< 300ppm	10m	2.0m

Damage Temperature to the Lining Structure

Tunnel fires often last long. The long high temperature will damage tunnel ceiling structure, result in structure degradation, and even affect the structural stability. The concrete surface starts to crack at 150~200℃. Although high strength concrete is used in shield tunnel ceiling, the possibility and depth of cracking in fire are relatively large without fireproofing disposal. The concrete cracking not only threats the rescue and escape, but also makes the steel directly expose to fire. Association of American National Standards and Testing points out that the intensity of high strength concrete began to decrease when the temperature reaches 380℃, and the loss of compressive strength will be up to 40% at 450℃.

The purpose of the tunnel fireproofing is to make the concrete structure maintain its integrity and stability in the fire by certain measures. In this paper, 380℃ was considered as the damage temperature of the lining structure.