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A numerical study on the influence of slope and curvature on smoke flow in special section tunnel with natural ventilation

Wenzhou Wang[1], Xianping Zhou[1], Zhigang Liu[1], Ya Liu[2], Wanfu Liu[2], Li Hong Zhao[3]

[1]The Administration Center of Zhuhai Link Line Project of Hong Kong-Zhuhai-Macau Bridge, Guangdong, China
[2]School of Mechanical Engineering, Tianjin University of Commerce, Tianjin, China
[3]China Academy of Building Research, Beijing, China

Abstract. In this study, a special section tunnel model was established by using FDS (Fire Dynamics Simulator). The influences of lope and curvature on smoke flow under natural ventilation have been studied. The results showed that under the condition of natural ventilation, the slope has some influences on the smoke flow in special section tunnel. The smoke spreading speed is accelerated along the upstream direction and decrease along the downstream direction due to buoyancy effect of slope. The steeper the tunnel, the more obvious the buoyancy effect. The curvature has little effect on the flow of flue gas.

1. Introduce fds software

The fire dynamics simulation software FDS is a kind of fire-driven by computational fluid dynamics (CFD) model. It is calculated by using the N-S equations, which are suitable for the calculation of low-velocity heat flow, especially in the event of fire. The core algorithm is establishing a clear predictor corrector system to ensure the accuracy in terms and space.

LES (Large Eddy Simulation) is used in FDS to deal with the problem of turbulence. FDS software using Smokeview visualization programs to display the results of the fire dynamics simulation, and it has solved a large number of fire engineering problems.

2. Establishment of a model of special section tunnel

2.1 Tables

The Gongbei tunnel includes three parts, the open cut section of the sea area, the hidden section of the port and the open cut section of the land. The straight line, transition curve and circle curve form the W-type tunnel plane. The longitudinal section slope is U-type from 2.412% to 0.35%, and then to 2.995%. The minimum curve radius of the road is 890m, the maximum longitudinal slope is 2.995%, and the minimum longitudinal slope is 0.35%. Plane graph of Gongbei tunnel is shown in Figure 1. Longitudinal section of Gongbei tunnel is shown in Figure 2

Figure 1. Plan graph of Gongbei tunnel

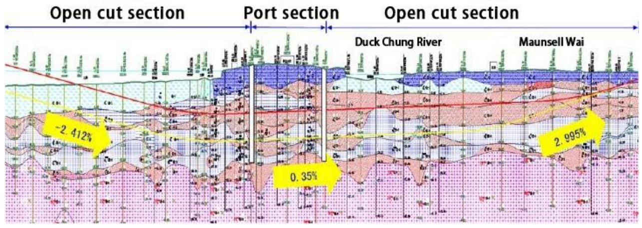


Figure 2. Longitudinal section of Gongbei tunnel

2.2 The Establishment of Calculation Model

According to the actual size of Gongbei tunnel, a simulation model is established which is shown in Figure 3. The physical model is selected from the pile number YK1+467.696 to YK3+582 segment, and the total length is 2114.304m.

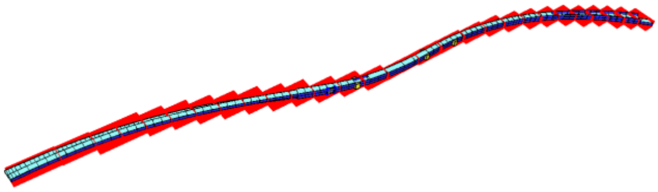


Figure 3: The simulation model of Gongbei tunnel

In addition, it is also an important step in the simulation process of FDS to divide the simulation computing area into the computational grid (Meshes), which directly affects the accuracy of the calculation results. The small size of the grid can improve the accuracy, but it will slow down the simulation speed and increase the calculation time. The large grid size can improve the simulation speed, but it will reduce the accuracy of the simulation. Therefore, considering the factors such as model size, computer configuration and the accuracy of calculation results, the mesh size in numerical simulation is 0.5m * 0.5m * 1m.The computational mesh is shown in Figure 4.

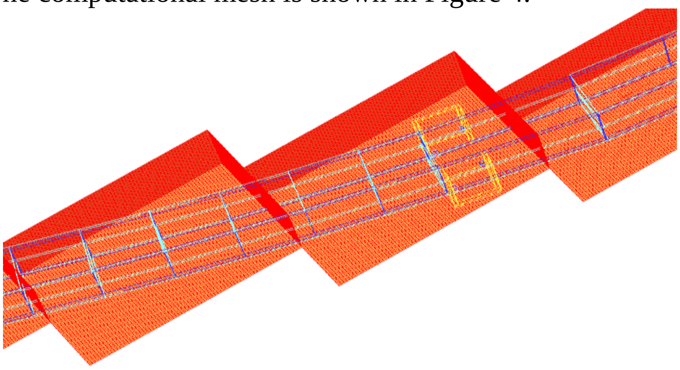


Figure 4: Computational mesh of Gongbei tunnel

In the process of designing the fire scene, the fire source is located in the building on the premise of taking full account of the geometric characteristics of the building. To ensure the accuracy of the fire location, it is necessary to take into account the possible scale of fire, the spatial characteristics of each functional area within the building, the distribution of evacuation exit and smoke control measures. In addition, the slope and curvature of the tunnel should be considered. Based on the above factors, 5 fire sources are located in the right line of the tunnel.

The location of fire is shown in Table 1. Schematic diagram of fire source location is shown in Figure 5.

Table 1. The location of fire

number	The location of fire	Height difference	Slope	curvature
B	HJD-35	11.083	-2.412%	1.22%
E	middle section	-1.566	0.350%	0.96%
F	LJD-08	-1.874	0.350%	0.47%
G	LJD-21	-5.469	0.350%	1.39%
H	LJD-35	-10.412	2.995%	1.13%

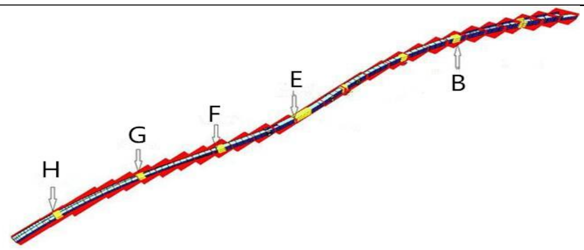


Figure 5: Schematic diagram of fire source location

In order to approach the actual situation, super- fast fire is selected, which fire growth rate is 0.1875 kW/s^2, the heat release rate is 50MW, and the combustion time is 516s. The plate size is 3m* m according to the grid precision and calculation model.

3. Simulation result analysis

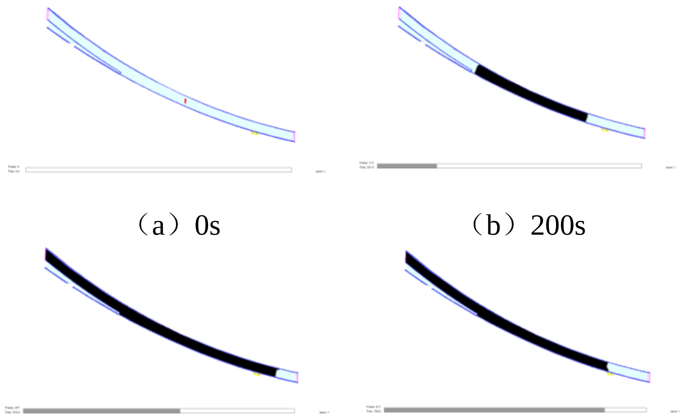
3.1 Influence of slope on flue gas flow under natural ventilation

Three different slope calculation conditions were selected and compared in order to study the influence of slope on the smoke flow. The slope is different but the curvature is similar. Other conditions on the effects of smoke flow are ignored. Selection of fire scene under natural ventilation is shown in Table 2.

Table 2: Selection of fire scene under natural ventilation

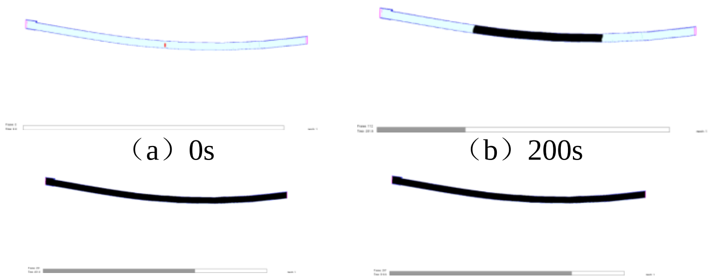
number	Heat release rate (MW)	Slope	Longitudinal wind velocity (m/s)
B	50	-2.412%	0
G	50	0.350%	0
H	50	2.995%	0

When the fire source is located at the slope of -2.412%, 0.350% and 2.995% of the tunnel, the natural ventilation conditions of the smoke spread as follows figure 6- figure 8. Sketch of smoke spreading in scene B is shown in Figure 6. Sketch of smoke spreading in scene G is shown in Figure 7. Sketch of smoke spreading in scene H is shown in Figure 8.



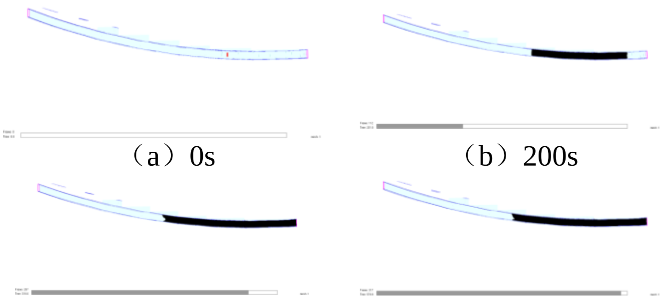
（a）0s （b）200s
（c）516s （d）750s

Figure 6: Sketch of smoke spreading in scene B. (a) 0s. (b) 200s. (c) 516s, the peak of heat release rate .(d) 750s, smoke spread length stability.



（a）0s （b）200s
（c）451s （d）516s

Figure 7: Sketch of smoke spreading in scene G. (a) 0s. (b) 200s. (c)451s, the smoke spread length exceeds the calculation model.(d) 516s, the peak of heat release rate .



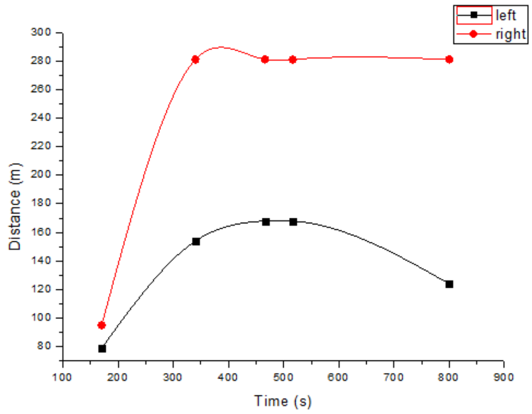
（a）0s （b）200s
（c）516s （d）570s

Figure 8: Sketch of smoke spreading in scene H. (a) 0s. (b) 200s. (c) 516s, the peak of heat release rate .(d) 570s, smoke spread length stability

As can be seen from Figure 6-Figure 8 that the smoke is rising in the form of an axis-symmetric plume. With the increase of time, the smoke reaches the ceiling, and then spreads under the ceiling.

The length of flue gas reaches stable at 750s in scene B. The smoke spread length exceeds the calculation model at 451s in scene G. The length of flue gas reaches stable at 570s in scene H.

According to the simulation results of FDS software, the smoke level spread distance and velocity of each scene can be analyzed. The results are shown in Figure 9- figure 11. Left indicates the upstream direction of fire source and Right indicates the downstream direction of fire.



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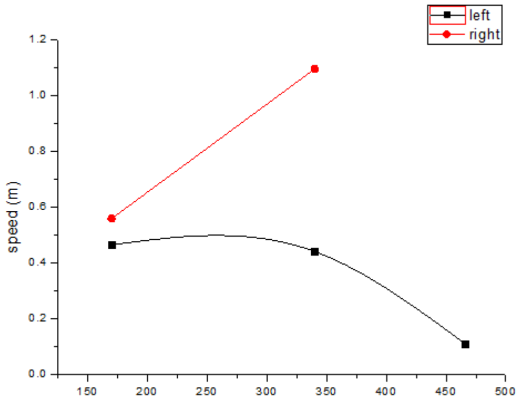
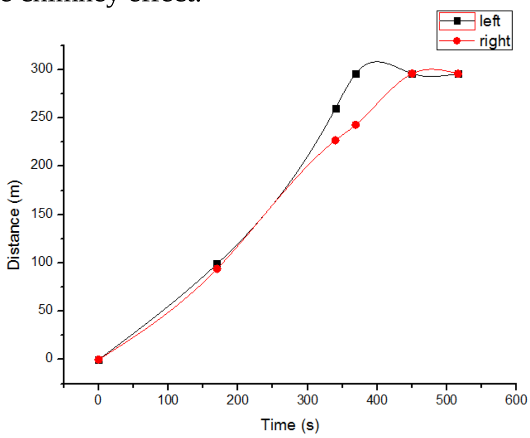


(b)

Figure 9: Smoke spread distance and speed in scene B. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 9 that smoke spread length of upstream reached peak at 466s in scene B. According to the results, the reflux length was 168 m, and the spreading speed was 0.361m/s. However, the downstream smoke spread rate was 0.826 m/s. This is due to the slope is -2.412% of the scene. Downstream smoke spread faster than the upstream because the thermal buoyancy. When the heat release rate reaches peak value and is stable, the reflux length of the flue gas is shortened and spread to the outlet due to the chimney effect.



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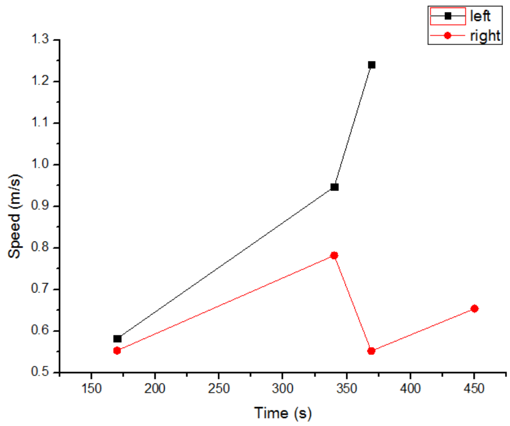
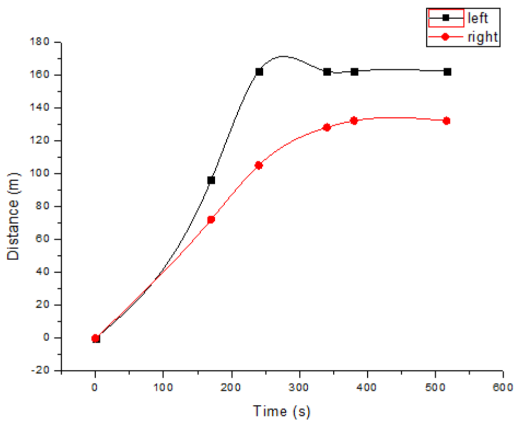


(b)

Figure 10: Smoke spread distance and speed in scene G. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 10 that smoke spread length of upstream reached peak at 369s in scene G. According to the results, the reflux length was 296 m, and the spreading speed was 0.802m/s. However, smoke spread length of downstream reached peak 296m at 450s, and the downstream smoke spread rate was 0.658 m/s.



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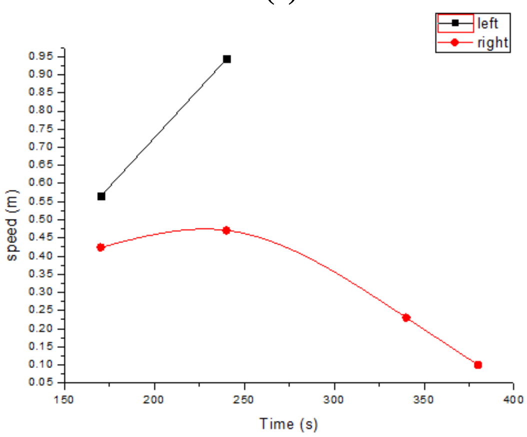


(b)

Figure 11: Smoke spread distance and speed in scene H. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 11 that smoke spread length of upstream reached peak 162m at 239s in scene H. According to the results, the spreading speed was 0.677m/s. However, smoke spread length of downstream reached peak 133m at 361s, and the downstream smoke spread rate was 0.368 m/s.

According to the results, under the condition of natural ventilation, the slope has some influences on the smoke flow in special section tunnel. Smoke spread along the tunnel sides are no longer symmetrical due to the existence of the slope. The smoke spreading speed is accelerated along the upstream direction and down along the downstream direction due to buoyancy effect of slope. The steeper the tunnel is, the more obvious the buoyancy effect is.

3.2 Influence of curvature on flue gas flow under natural ventilation

Three different slope calculation conditions were selected and compared in order to study the influence of curvature on the smoke flow. The curvature is different and the slope is similar. Other conditions on the effects of smoke flow are ignored. Selection of fire scene under natural ventilation is shown in Table 3.

Table 3: Selection of fire scene under natural ventilation

number	Heat release rate MW	curvature	Longitudinal wind velocity (m/s)
E	50	0.96%	0
F	50	0.47%	0
G	50	1.39%	0

When the fire source is located at the curvature of -0.96%, 0.47% and 1.39% of the tunnel, the natural ventilation conditions of the smoke spread as follows figure 12- figure 14. Sketch of smoke spreading in scene E is shown in Figure 12. Sketch of smoke spreading in scene F is shown in Figure 13. Sketch of smoke spreading in scene G is shown in Figure 14.

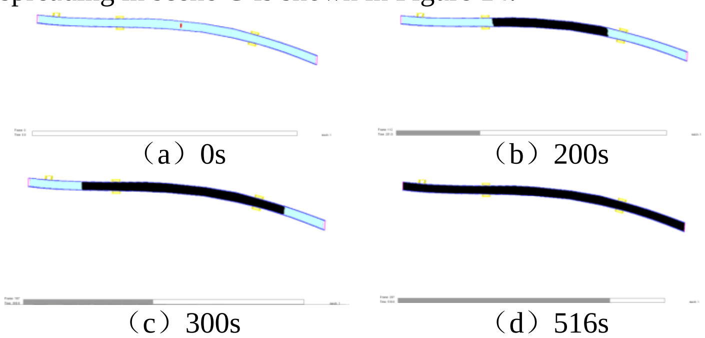


Figure 12: Sketch of smoke spreading in scene E. (a) 0s. (b) 200s. (c) 300s. (d)516s, the peak of heat release rate .

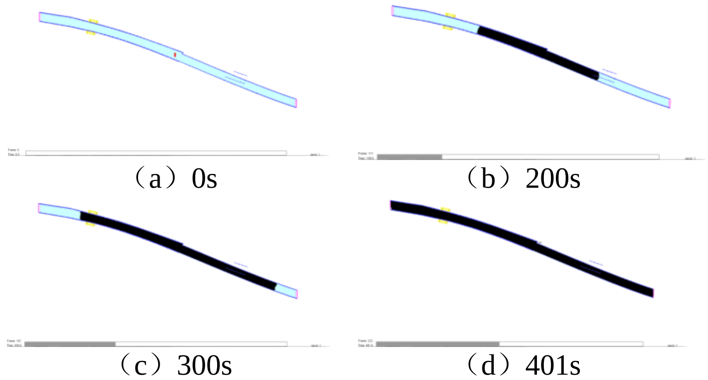


Figure 13: Sketch of smoke spreading in scene F. (a) 0s. (b) 200s. (c) 300s. (d) 401s, the smoke spread length exceeds the calculation model.

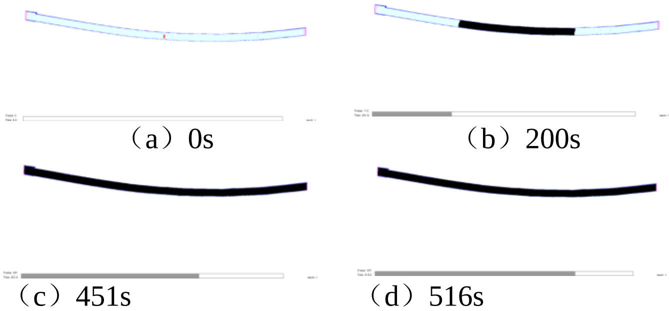
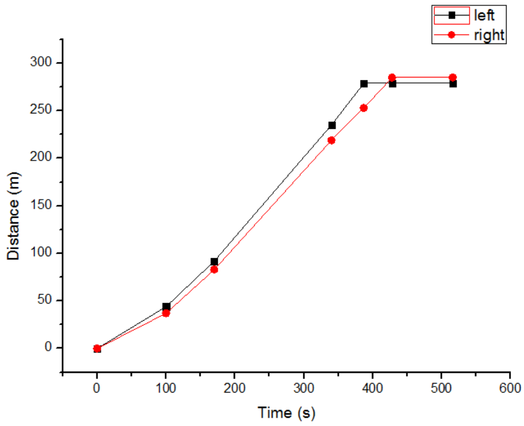


Figure 14: Sketch of smoke spreading in scene G. (a) 0s. (b) 200s. (c) 451s, the smoke spread length exceeds the calculation model . (d) 561s, the peak of heat release rate .

As can be seen from Figure 12-Figure 14 that the smoke is rising in the form of an axis-symmetric plume. With the increase of time, the smoke reaches the ceiling, and then spreads under the ceiling.

The smoke spread length exceeds the calculation model at 401s in scene F. The smoke spread length exceeds the calculation model at 451s in scene G

According to the simulation results of FDS software, the smoke level spread distance and velocity of each scene can be analyzed. The results are shown in Figure 15- figure 17. Left indicates the up-stream direction of fire source and Right indicates the downstream direction of fire.



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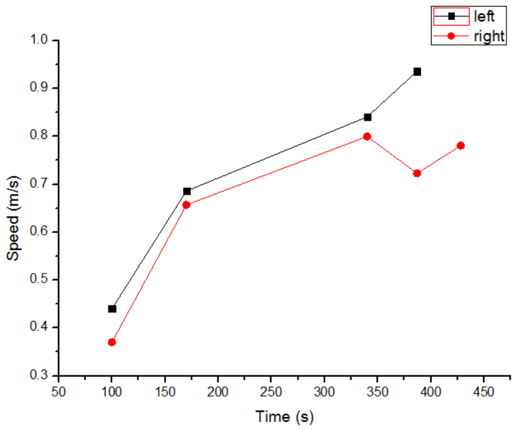
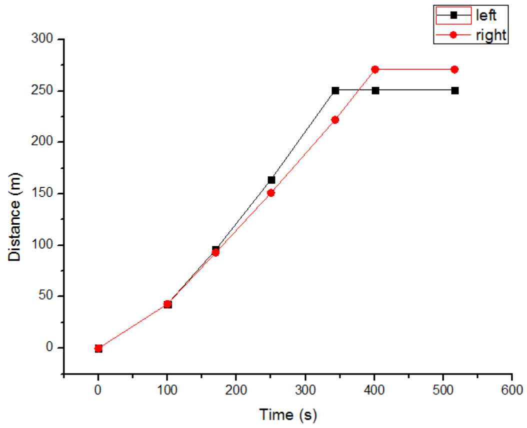


(b)

Figure 15: Smoke spread distance and speed in scene E. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 15 that smoke spread length of upstream reached peak at 387s in scene E. According to the results, the reflux length was 279 m, and the spreading speed was 0.721m/s. How-ever, smoke spread length of downstream reached peak 285m at 428s, and the downstream smoke spread rate was 0.666 m/s.



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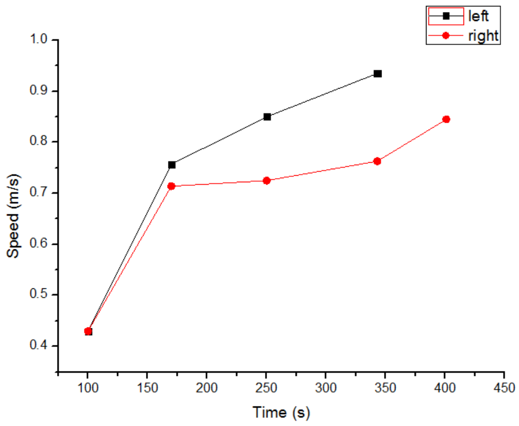
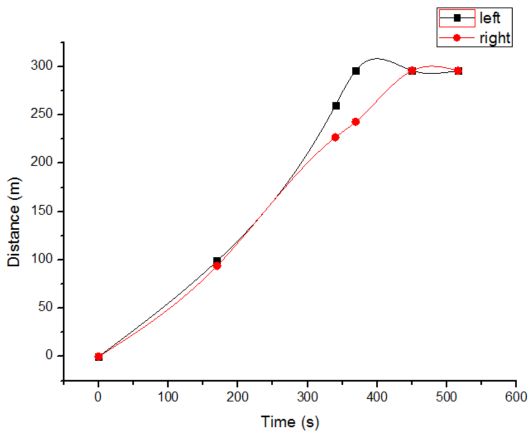


(b)

Figure 16: Smoke spread distance and speed in scene F. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 16 that smoke spread length of upstream reached peak at 343s in scene F. According to the results, the reflux length was 251 m, and the spreading speed was 0.732m/s. However, smoke spread length of downstream reached peak 271m at 401s, and the downstream smoke spread rate was 0.676 m/s.



(a)

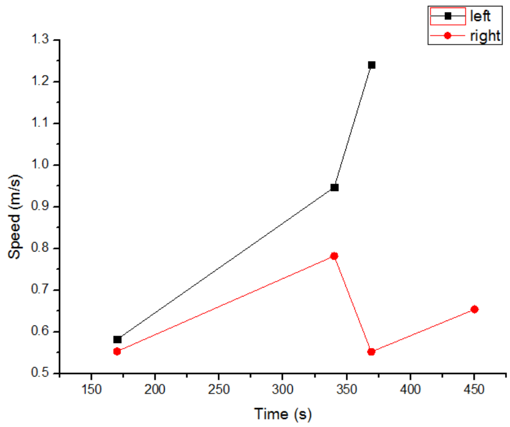


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Figure 17: Smoke spread distance and speed in scene G. (a) Smoke spread distance. (b) Smoke spread speed.

As can be seen from Figure 17 that smoke spread length of upstream reached peak at 369s in scene G. According to the results, the reflux length was 296 m, and the spreading speed was 0.802m/s. However, smoke spread length of downstream reached peak 296m at 450s, and the downstream smoke spread rate was 0.658 m/s.

Comparing with the spread rate of flue gas under different curvature, it can be seen that, the curvature has little effect on the flow of flue gas. However, the spreading speed of upstream flue gas does not meet this law in scene G. That is because the scene G position is closer to the entrance than the E scene and F scene. The entrance slope is greater than the scene E, F, G. Due to the strong "chimney effect" makes the upstream smoke of scene G spread faster than the scene E and scene F.

4. Conclusions

In this study, a special section tunnel was established by using FDS (Fire Dynamics Simulator). The influences of lope and curvature on smoke flow under natural ventilation have been studied. The results showed that:

(1) Under the condition of natural ventilation, the slope has some influences on the smoke flow in special section tunnel. Smoke spread along the tunnel sides are no longer symmetrical due to the existence of the slope. The smoke spreading speed is accelerated along the upstream direction and down along the downstream direction due to buoyancy effect of slope. The steeper the tunnel is, the more obvious the buoyancy effect is.

(2) Comparing with the spread rate of flue gas under different curvature, it can be seen that, the curvature has little effect on the flow of flue gas.

Acknowledgements

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