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Numerical study on fire smoke movement and control in curved road tunnels

Feng Wang[a,b], Mingnian Wang[a], Ricky Carvel[b], Yu Wang[a],

[a] Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, School of Civil Engineering,
Southwest Jiaotong University, Chengdu 610031, China;

[b] Institute for Infrastructure and Environment, School of Engineering, University of Edinburgh,
Edinburgh, EH9 3JL, Scotland UK

Abstract: This study presents numerical results for critical ventilation velocity and smoke movement for fires in different transverse positions in curved tunnels. The highest critical velocity is observed for a fire positioned next to the convex wall in a curved tunnel where the critical velocity is 16% higher than a fire located centrally in the same curved tunnel which has a curvature radius of 600 m. Critical velocity is observed to vary slightly with curvature, being 7% larger in a 400 m radius tunnel compared to a fire in a straight tunnel. This could be attributed to generally lower speed flows near the convex wall in curved tunnels, and this effect diminishes with larger curve radii. As a consequence, higher smoke temperatures at the ceiling are found for fires near the convex wall in curved tunnels, and tunnel ventilation speed has to be increased to prevent the smoke back-layering in curved tunnels. Additionally, three regimes of back-layering length are concluded for the transverse fire locations in this paper. The first is for a fire next to the tunnel wall, where the back-layering length increases slowly as the air speed tends to be lower than the critical velocity, followed by a rapid rise. Secondly, as a fire moving away from the wall, the back-layering length increases at a gentle gradient. The back-layering length is shortest in this circumstance. A fire in the middle lane and a fire in the lane near convex wall are considered as regime 3. The back-layering length evolution is steepest. Here the back-layering length increases significantly as the tunnel curve radius decreases for the same air speed.

Keywords: curved tunnels, tunnel fire, critical velocity, smoke movement

1 Introduction

Road tunnel fire prevention, fire fighting, evacuation of tunnel users, fire damage to tunnel lining, etc. are continuing to attract considerable attentions from the international research community due to the significant losses of life in tunnel fire accidents, and the resulting economic losses (Lonnermark, 2005; Sakkas et al., 2014). Tunnel fires, however, are very complex phenomena because of the interactions between the fire dynamic process (for example turbulence, combustion, radiation, etc.) and the tunnel geometry (such as tunnel shape, vehicle geometry, arrangement of vehicles, etc.). Some road tunnel fire projects have been carried out around the world, such as the EUREKA project where nine European nations cooperated, the FIT project and the UPTUN

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project (Haack, 1998; FIT, 2003; Hejny, 2005). These projects have significantly improved our understanding of fires in the road tunnels.

This present study is focused on fires in curved tunnels due to their special horizontal shapes. Because of topographic constraints, many road tunnels are constructed curved in a horizontal plane even with small curve radius. For instance, there are two road tunnels in Sichuan province in China with a minimum curve radius of 600 m and a horizontal angle of approximate 280 degree, and another curved road tunnel in Yunnan province in China with a curve radius of 561 m. Given that the majority of previous road tunnel fire studies have focused on straight tunnels, the influence of curvature on smoke control has not been adequately understood. Accordingly, authors of this paper have previously conducted research on normal ventilation in curved tunnels and some interesting findings have already been presented (Wang et al., 2012). For example, an asymmetrical airflow was observed in a curved tunnel, and it was observed that the curved wall caused a boundary layer flow downstream of the jet fans. Subsequently, an optimal distribution of jet fans was proposed to improve the pressure-rise in the curved tunnel. In addition, the traffic force was also investigated using CFD (Computational Fluid Dynamics) and 1D (One-dimensional) models in curved tunnels. The traffic force was found to increase with a decrease of tunnel curve radius. The CFD results were then used to improve the 1D traffic force model (Wang et al., 2014). These findings have improved our understanding of normal ventilation in curved tunnels.

When fires occur in curved tunnels, the hot smoke will spread under the constraint of the asymmetrical tunnel wall boundary, as well as the asymmetrical airflow. These factors will make the smoke movement significantly different from that in a straight tunnel fire, and the curvature should be considered fully when designing smoke control system. Therefore, there is clearly a need for analyzing the smoke movement in curved tunnels.

As is well known, considerable attention has been concentrated on critical ventilation velocity for fires in straight tunnels in the last few decades. As a result of these studies, some critical velocity models have been developed from theoretical, experimental and numerical studies. The earliest expression of critical velocity, through a theory based on the Froude number preservation, was proposed by Thomas (Thomas, 1958). He suggested the balance between the buoyancy and inertia forces was a critical condition during a tunnel fire. The relationship between critical velocity and heat release rate was accordingly expressed as follows:

$$V_c = \left(\frac{gHQ}{\rho_0 T_f c_p A}\right)^{1/3} \qquad (1)$$

where V_c is critical velocity, g is gravitational acceleration, H is tunnel height, Q is heat release rate, ρ_0 is ambient density, T_f is gas temperature, c_p is thermal capacity of air, and A is tunnel cross-section area.

This model physically explains the tunnel smoke flow phenomena quite well, given the limitation of the assumptions made. An improved model was subsequently proposed by Danziger and Kennedy, who suggested that the Froude number should have a value of 4.5 (Danzeger and Kennedy, 1982).

Subsequently, some experimental studies have been conducted and some new findings have been presented. Oka and Atkinson (1995) proposed two regimes of critical velocity for various heat release rates under tunnel fires. The work was extended by Wu and Bakar (2000) using small-scale experiments. One of their findings is that the hydraulic diameter should be used as the length-scale for scaling applications. Their critical velocity model, expressed in non-dimensional quantities, is defined as:

$$V_c' = 0.40\left(\frac{Q'}{0.20}\right)^{1/3} \qquad \text{for } Q' \le 0.20$$

$$V_c' = 0.40 \qquad \text{for } Q' > 0.20 \qquad (2)$$

Where $V_c' = \frac{V_c}{\sqrt{g\overline{H}}}, Q' = \frac{Q}{\rho_0 c_p T_0 g^{1/2} \overline{H}^{5/2}}, \overline{H}$ is hydraulic diameter. T_0 is ambient temperature.

Recently, some critical velocity models have been developed using field fire tests by Hu et al. (2008) and experimentally by Li et al. (2010). However, it is noted that some detailed factors, for instance the influence of tunnel shape, tunnel blockage and tunnel slope cannot be resolved from these above models. Other studies have been subsequently carried out as well. Lee and Ryou (2006) numerically studied the effect of aspect ratio on critical velocity. They found that the growth and development of smoke were affected by the aspect ratio of tunnel cross-section. The critical velocity increased with the increase of the aspect ratio as well. Chow et al. (2010,2015) introduced an empirical critical velocity model and smoke movement pattern in a tilted tunnel in numerical and experimental studies. Ji et al (2012) investigated the influence of different transverse fire locations on maximum smoke temperature under the tunnel ceiling. Lee and Tsai (2012) and Soufien and Rejeb (2015) carried experimental and numerical studies, respectively, on the effect of vehicular blockage on critical velocity.

All of their studies found that the critical ventilation velocity decreased as the vehicle blockage ratio for vehicles positioned upstream of fire.

Additionally, numerical studies were also used to predict or reproduce various tunnel fire scenarios. Vega et al. (2008) used the FLUENT code to reproduce the Memorial tunnel fire experiments. The numerical results showed a reasonably good agreement with the experimental results. Betta et al. (2010) proposed a 'Banana' jet fan and an optimal pitch angle at a tunnel fire ventilation using CFD. A study investigating the effects of the location of jet fans in a tunnel fire has been described by Se et al. (2012). They found that a distance of more than 200 m between an active fan group and the fire was needed for fully developed airflow.

These above studies have primarily focused on fires in straight tunnels. However, until now there has not been study of fires in curved tunnels available. In the light of this, the paper will present numerical details under curved tunnel fires.

2 Model description

2.1 Mathematical description

The commercial computational fluid dynamics software package, FLUENT v. 6.3.26, was employed to solve the continuity, momentum and energy equations, together with the turbulence model in the present work. The RNG k-ε turbulence model was adopted due to its improved accuracy for rapidly strained flows and swirling flows through modifying the turbulent viscosity appropriately (Fluent user's guide, 2006). The gravitational body force was embodied in the momentum equations by defining buoyancy terms as a function of temperature variations according to the Boussinesq approach. Additional numerical technique details can be found in the previous study (Wang et al., 2016). It is worth noting that the fire is modeled as a volumetric heat source (VHS) instead of including complicated combustion chemical reactions. As high computing power is required for radiation simulation, a 35% reduction of the total heat input was applied to the fire and radiation was not modeled in accordance with the proposals made by the PIARC Committee on Road tunnels (PIARC, 1999). This approximation has been shown to give acceptable results in the study by Vega et al. (2008).

2.2 Physical model

The models used were curved tunnels, with a length of 300 m and with various radii. The fire was modeled as a rectangular prism of 4.5 m ×1.4 m ×1.4 m at various transverse fire locations and at a longitudinal distance of 150 m to guarantee a fully developed flow, as shown in Fig.1. The cross-section of the modeled tunnel was 68.55 m^2 with a hydraulic diameter of D_t=8.57 m as shown in Fig.2. The mass flow rate of the combustion products was released in the domain on the upper surface of the prism. The mass flow rate was estimated using the expression proposed by Vega et al. (2008).

$$m_g = \frac{Q}{c_p(T_f - T_0)} \qquad (3)$$

Where m_g represents gas mass flow rate.

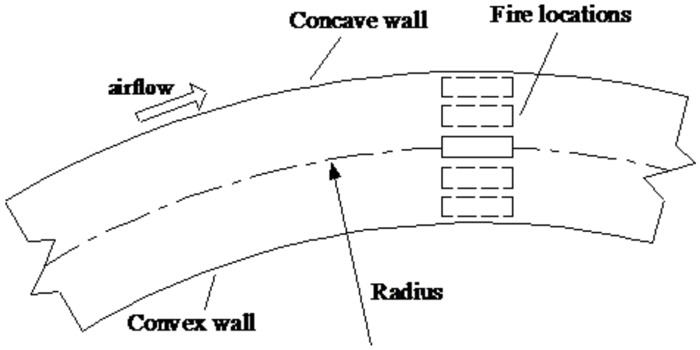

Fig.1. Sketch of the fire locations in curved tunnels

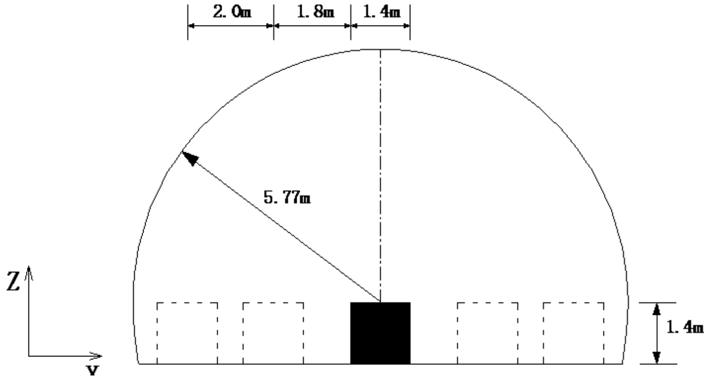

Fig.2. Tunnel cross-section

2.3 Grid sensitivity and validation

A structured mesh was applied all over the computational domain. The mesh was refined longitudinally in the vicinity of the tunnel fire, to resolve the extremely complicated flow field. Several different mesh sizes on the cross-section were investigated to assure grid-independent results. The detailed mesh sensitivity study can be found in the previous study (Wang, 2016). The mesh consisting of 2,015,853 cells in total was chosen for the presented simulations, due to an acceptable compromise between the accuracy of the results and the computational cost.

The Memorial tunnel fire Test No. 606 A was simulated using the described computational model. The arrangement of the experimental and numerical model can be found in the study by Kelly and Giblin (1997). A detailed comparison of smoke temperature and velocity at 681.5 m from the north portal can also be found in the previous study (Wang, 2016). The prediction of smoke temperatures agrees acceptably well with the experimental results. The velocity profile predicted generally shows a good agreement except in the bottom region. The 35% reduction of the heat release rate in the CFD model is believed to responsible for these local differences, as discussed by Vega et al (2008). Consequently, it is concluded that the model produces acceptable results through comparison with experiments.

2.4 Boundary conditions and simulation details

The 10 MW fire was described using a VHS model. The wall boundary condition was taken to be adiabatic, and was applied on the solid walls of tunnel. A velocity boundary condition was prescribed at the tunnel entrance. A free pressure outlet boundary condition was used for the tunnel exit. The temperatures of the combustion gases and the ambient air were assumed to be 300 ℃ and 12 ℃, respectively. All simulations were carried out on a personal computer with a 3.2 GHz Dual Core CPU and 16 GB RAM. The convergence criteria was set at 10^{-3}. The detailed simulated cases are listed in Table 1.

Table 1 Simulation cases

R(m)	Fire location	Ventilation velocity (m/s)
400	Next to the convex wall	2.7,2.8,2.9,3.0
600	Next to the concave wall	2.3,2.4,2.5,2.6,2.7,2.8
	In the lane near the concave wall	2.3,2.4,2.5
	In the middle	2.3,2.4,2.5
	In the lane near the convex wall	2.3,2.4,2.5,2.6
	Next to the convex wall	2.3,2.4,2.5,2.6,2.7,2.8,2.9
1200	Next to the convex wall	2.6,2.7,2.8,2.9
2000	Next to the convex wall	2.5,2.6,2.7,2.8

3 Results and discussion

3.1 Critical velocity

In this study, smoke temperature is used to investigate the smoke behaviour. The effects of transverse fire locations on critical velocity are analyzed initially for a curved tunnel with a radius of 600 m. The analysis then extends the study to other radii.

The temperature contours on the wall for various transverse fire locations in the curved tunnel are shown in Fig.3. It can be found that the critical velocity is 2.9 m/s for a fire next to the convex wall, which is slightly higher than the identified critical velocity of 2.8 m/s for a fire next to the concave wall. The critical velocity is found to be 2.6 m/s for a fire in the lane near the convex wall whereas the critical velocity is found to be 2.5 m/s for a fire in the lane near the concave wall or in the middle lane. It is apparent that the distribution is not symmetrical, the critical velocity for a fire near the convex wall is slightly higher than for a fire near the concave wall. A careful examination is concentrated on the smoke movement. The high-temperature smoke at the downstream exhibits a wave flow in the curved tunnel. The wall temperature near the fire is observed to be highest for a fire next to the concave wall and convex wall, followed by a fire in the lane near concave and convex wall and then in the middle.

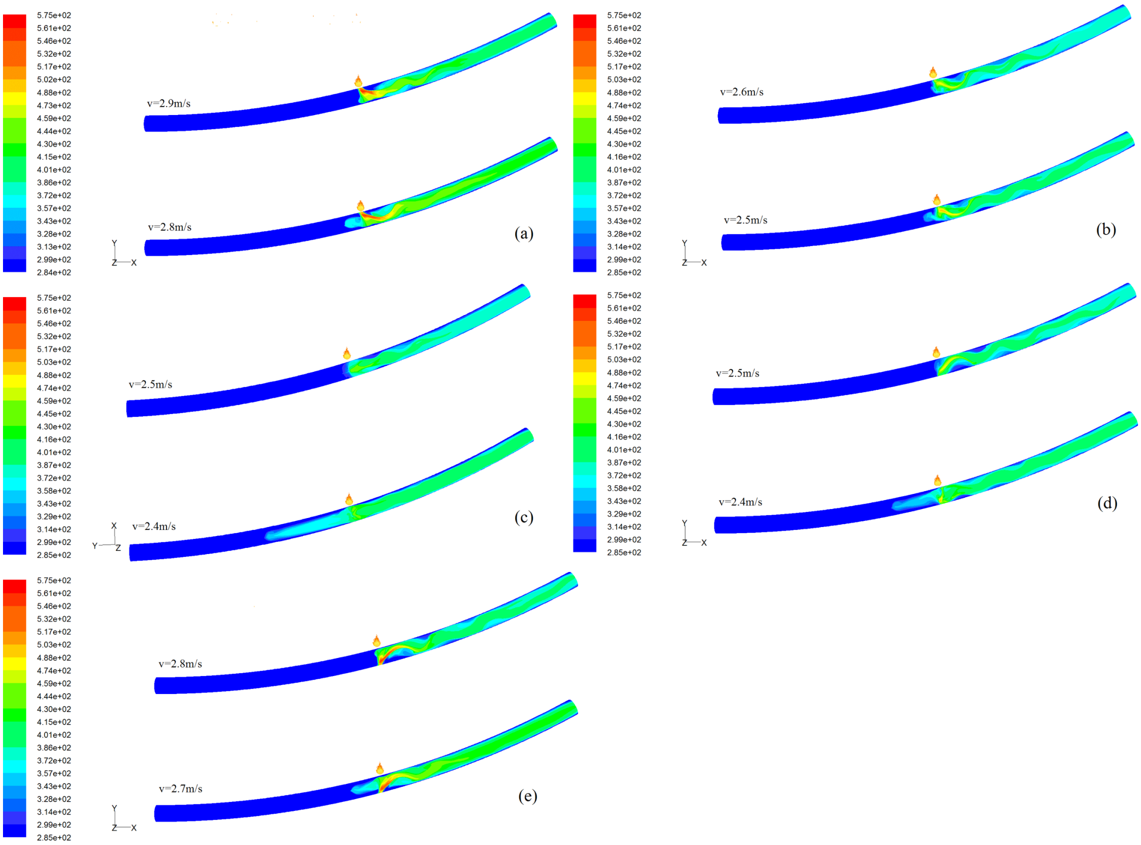

Fig.3 Temperature contours on the wall for various fire locations: (a) next to convex wall; (b) in the lane near convex wall; (c) in the middle; (d) in the lane near concave wall; (e) next to concave wall

The critical velocities for various transverse fires in the curved tunnel are subsequently compared with those for a straight tunnel fire, the model of Thomas, and Wu and Bakar, as shown in Table 2. It can be seen that the critical velocity for a fire located in the middle and near the concave wall in the curved tunnel is essentially the same as that in the straight tunnel, whereas the critical velocity for fires near the convex wall is slightly higher. Conversely, the CFD results for a centrally located fire both in the curved and straight tunnels are found to be close to Thomas's result and significantly greater than the prediction from Wu and Bakar's model. The Wu and Bakar model is considered to be applicable for a large tunnel fire, whereas the fire in the middle lane used in this study is essentially a small fire, as discussed in the previous study (Wang, 2016). As a consequence, the predictions of Thomas's model exhibit a good agreement for a middle fire. But the Thomas model is not able to predict the critical velocity for a fire next to a wall in a curved tunnel.

Table 2 Comparison of the critical velocity

Critical velocity models			critical velocity (m/s)
CFD results	R=600m	Next to the convex wall	2.9
		In the lane near the convex wall	2.6
		In the middle	2.5
		In the lane near the concave wall	2.5
		Next to the concave wall	2.8
	straight tunnel	Next to the wall	2.8
		In the lane near the wall	2.5
		In the middle	2.5
Thomas			2.46
Wu and Bakar			2.20

Fig.4 shows the variation of critical velocity ratio with the dimensionless widthwise coordinate, where V_{cm} is the critical velocity for a middle fire and the negative value of d/D represents the deviation from the middle to the convex wall, vice versa.

In Fig. 4 an asymmetrical critical velocity profile is apparent for the curved tunnel. The critical velocity ratio increases significantly as the fire is moved towards a wall in a straight or curved tunnel. Clearly, the ratio rises more prominently for fires near the convex wall in the curved tunnel. Accordingly, the critical velocity for a fire near the convex wall is observed to be higher than that in a straight tunnel or fires near the concave wall. The peak ratio is 1.16 for a fire next to the convex wall in this curved tunnel.

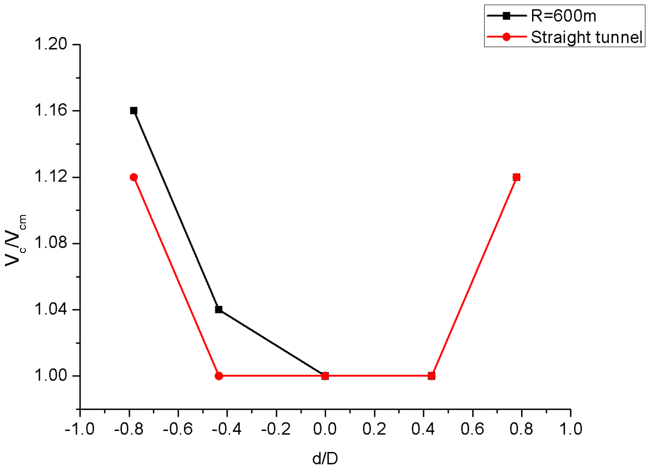

Fig.4 Critical velocity variation

Simulation of a fire next to the convex wall is also conducted for curved tunnels of various radii, as shown in Fig.5. It can be observed that the critical velocity rises to 3.0 m/s for a curved tunnel with a radius of 400 m, followed by a critical velocity of 2.9 m/s in the curved tunnels of radius of 600 m and 1200 m. It is noted that a same critical velocity of 2.8 m/s as straight tunnel is observed for the curved tunnel with a radius of 2000 m. Thus it may be concluded that for tunnels with a radius smaller than 2000 m, the critical velocity next to the convex wall exhibits a slight growth with decreasing radius, with a maximum effect of 7% higher with a 400 m radius.

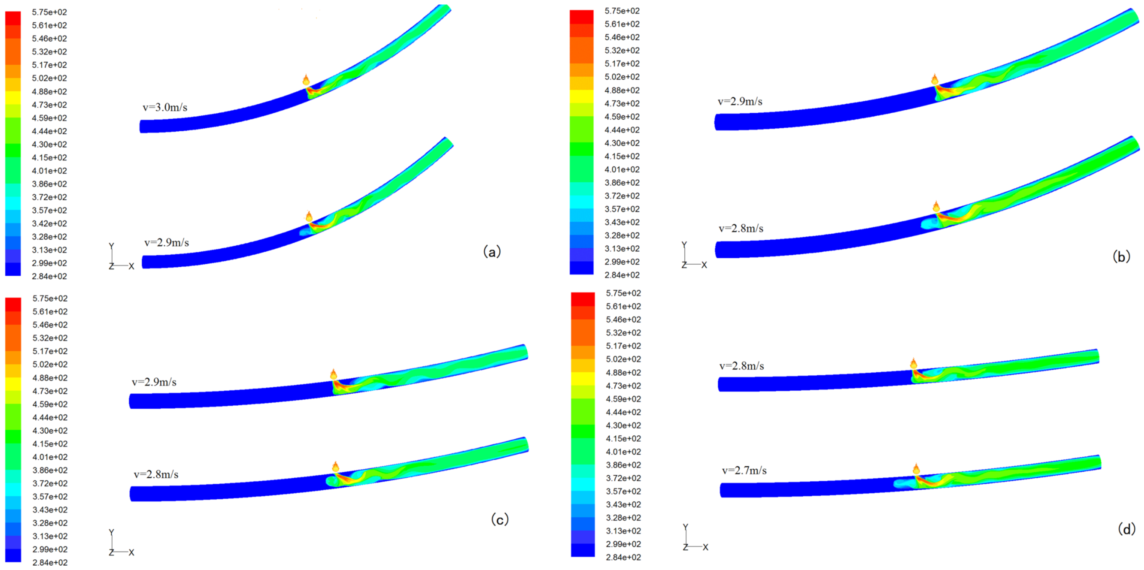

Fig.5 Temperature contours on the wall for various radii: (a)R=400m; (b) R=600m; (c) R=1200m; (d) R=2000m

3.2 Back-layering length

The back-layering length is very important for evacuation and firefighting, and accordingly attracts our attention to the back-layering length evolution in curved tunnels. Fig.6 shows the detailed back-layering lengths for various transverse fires in the curved tunnel with a radius of 600 m as well as the straight tunnel. The solid and dashed lines represent the curved tunnel and the straight tunnel, respectively. It can be found there are three regimes of the back-layering length evolution. Firstly, as for a fire next to the tunnel wall, the back-layering length increases slowly when air speed initially lower than the critical velocity, followed by a rapid rise. In this regime, the back-layering length for a fire next to the convex wall is greater than for a fire next to the concave wall or in a straight tunnel. This fire scenario is regarded as a big fire in the previous study (Wang, 2016). The second is for a fire in the lane near concave wall or near wall in a straight tunnel. The back-layering length increases monotonously with the decrease of the air speed. The back-layering length in a straight tunnel is slightly higher than that in a curved tunnel. Also, the back-layering length is significantly lower than a fire next to tunnel wall. A middle fire and a fire in the lane near convex wall are regarded as regime 3. The variation is steepest, namely the back-layering length increases considerably with the decrease of the air speed. Consequently, the back-layering length almost arrives at the proximity of a fire next to the convex wall at 2.3 m/s. In addition, the back-layering length for the middle fire in the curved tunnel overshoots that for the middle fire in the straight tunnel.

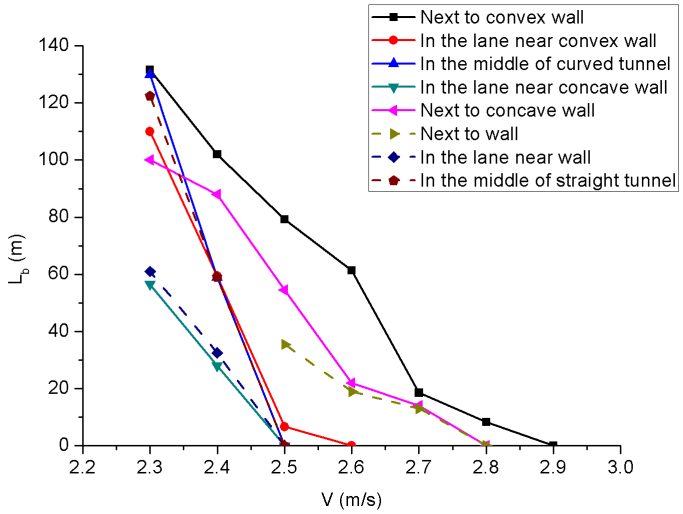

Fig.6 Back-layering length for various fire locations

Normally, the back-layering length is believed to be small enough as it is less than 20 m, and it does not impair strongly the firefighting by firemen. As a result, It would make sense to control the fire smoke back-layering length less than 20 m. It can be found that the back-layering length overshoots 20 m quickly for a middle fire and a fire in the lane near walls when the air speed initially lower than the critical velocity. However, when the air speed is greater than 2.6 m/s at a fire next to the concave wall and a fire next to wall in the straight tunnel, as well as the air speed higher than 2.7 m/s at a fire next to the convex wall, the back-layering length is observed to be smaller than 20 m. Consequently, the air speeds have to be higher than the velocity values mentioned above in order to meet the need for firefighting in the curved tunnel and the straight tunnel.

Fig.7 shows the back-layering lengths for fires next to the convex wall in curved tunnels with various radii. Clearly, these back-layering length evolutions are included in regime 1. It should be noted that the back-layering length increases significantly with the decrease of radius at the same air speed. Similarly, in order to meet the firefighting, a minimum air speed of 2.8 m/s is needed for promising the less than 20 m back-layering length in the curved tunnel of R=400 m, whereas a minimum air speed of 2.7 m/s for curved tunnels of R=600 m, 1200 m, and 2000 m, as well as 2.6 m/s for the straight tunnel.

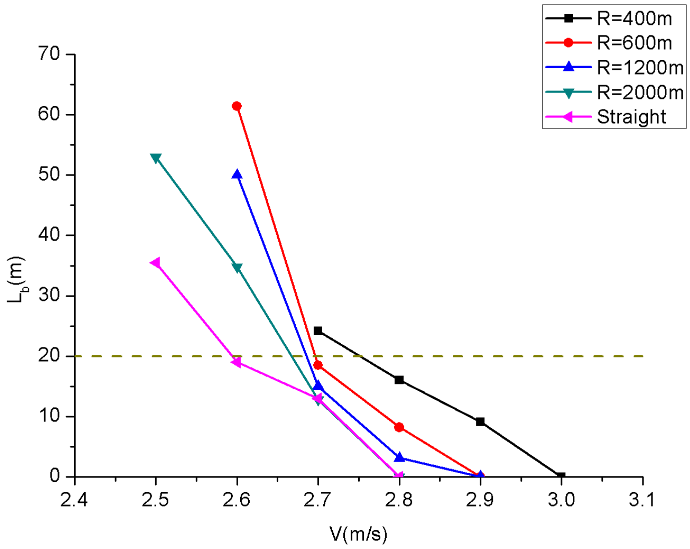

Fig.7 Back-layering length for various radii

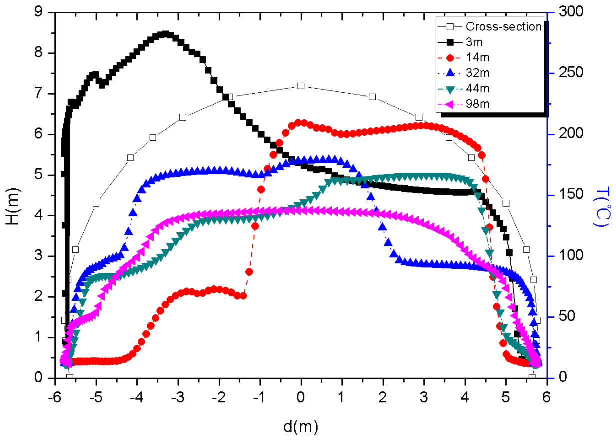

Fig.8 Smoke temperature on the wall for a fire next to the convex wall

3.3 Smoke movement and maximum smoke temperature under the ceiling

Firstly, the temperature profiles of the tunnel wall at the downstream for a fire next to the convex wall is employed to understand the smoke movement in the curved tunnel with a radius of 600 m as shown in Fig. 8. The maximum temperature can be found initially in the hance and spandrel of the convex wall which is just above the fire pool. The high-temperature smoke subsequently moves towards the top and the spandrel of concave wall. The following is the bidirectional sway of the high-temperature smoke till the layered hot smoke near the top. The smoke temperature decreases gradually as well. This phenomena is also observed at a fire next to the wall in a straight tunnel. And it could be explained through an equilibrium between a lateral inertia induced by hot smoke buoyancy and a friction.

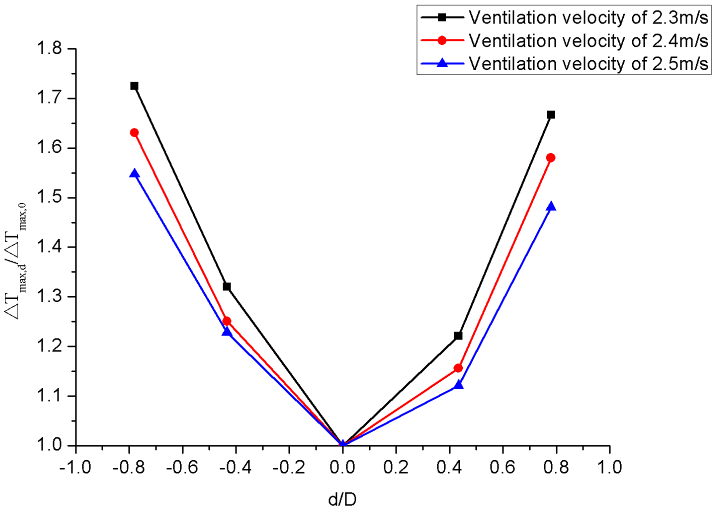

Fig.9 Maximum smoke temperature rise for various transverse fire locations in the curved tunnel

In order to understand the effect of transverse fire locations, a dimensionless maximum temperature rise on the top wall normalized by the maximum temperature rise of a middle fire is introduced in the curved tunnel with a radius of 600 m under various ventilation velocities, as seen in Fig.9, where $\triangle T_{max,0}$ is the maximum temperature rise at a middle fire and $\triangle T_{max,d}$ represents those with various transverse fire locations. The maximum temperature rise increases significantly as the fire pool moves towards the sidewalls also found by Ji (2012) where the restriction of the surrounding to the air entrainment of the fire plume is concluded in the rectangle cross-section. Here, another effect is needed to be considered that the vertical journey of the air entrainment of the fire plume decreases gradually when a fire moving towards the wall in horseshoe cross-section tunnels. Consequently, this maximum temperature rise is higher than that in Ji's study (2012) for wall fires. Additionally, It is noted that the maximum temperature rise for fires near the convex wall is evidently greater than that for fires near the concave wall which accordingly causes a higher critical velocity. The likely cause is a higher surrounding air speed near the concave wall which will be discussed in next section.

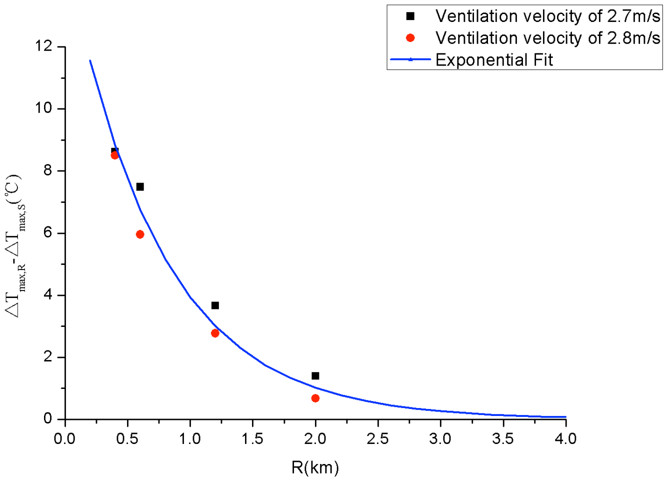

Fig.10 Maximum smoke temperature difference for various radii

Subsequently, the difference in the maximum temperature rise between curved tunnels and a straight tunnel is drawn for different ventilation velocities to assess the effect of the curvature, where ventilation velocities of 2.7 m/s and 2.8 m/s are adopted here, as in Fig.10. It can be found that the maximum temperature rise $\triangle T_{max,R}$ in curved tunnels is greater than $\triangle T_{max,S}$ in a straight tunnel, and the difference falls down exponentially with the increase of the curve radius. As a result, a tiny temperature difference is observed as the curve radius is more than 2000 m. Finally, a greater temperature rise will result in an increase of smoke heat buoyancy in a curved tunnel with smaller radius.

3.4 Velocity profile

The further work is concentrated on the air speed of incoming flow in curved tunnels. The velocity profiles are plotted horizontally at different heights of H=2.5 m and 4 m in the curved tunnel with a radius of 600 m as seen in Fig.11, where the velocity is normalized by the cross-sectional averaged velocity designated with v_a. Clearly, an asymmetrical velocity profile is observed in the curved tunnel and the peak is at d/D=0.43. The lower surrounding air speed will diminish the heat convection of the fire plume, and accordingly cause an increase in the maximum smoke temperature rise as well as the heat buoyancy. In the other hand, the local ventilation inertia would reduce with the decrease of the surrounding air speed. As a consequence, the ventilation velocity has to be improved to suppress the back-layer for wall fires and the biggest critical velocity is at a fire next to the convex wall in the curved tunnel. The velocity next to the convex wall at the heights of H=2.5 m and 4 m is also employed to explain the effect of curvature as shown in Fig.12, where the velocity is normalized using the corresponding straight tunnel velocity described with v_s. The velocity increases significantly with the increase of radius. This tends to be gradual as the radius is greater than 1200 m.

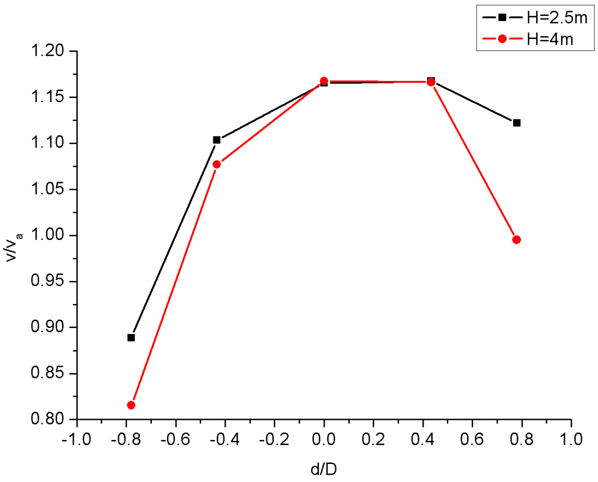

Fig.11Velocity profiles on the cross-section in the curved tunnel

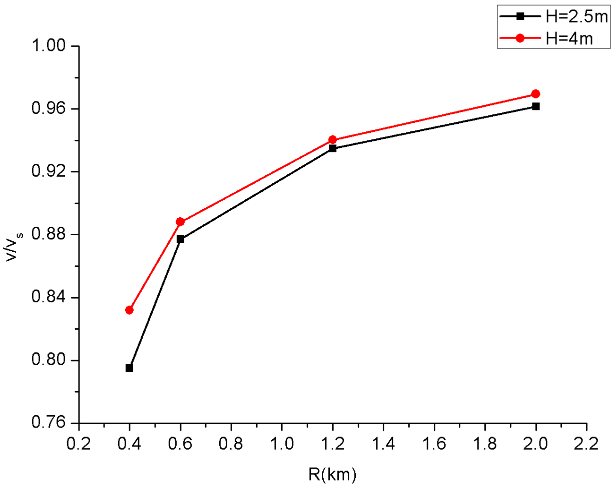

Fig.12 Velocity profiles for various radii

4 Conclusions

This study presents numerical results of critical velocity and smoke movement in curved tunnels. These results are subsequently compared with straight tunnel fires. It can be found that the critical velocity for a fire near the convex wall is significantly higher than other transverse fires in a curved tunnel. The peak critical velocity ratio is 1.16 at a fire next to the convex wall in the curved tunnel with a radius of 600 m. Additionally, the critical velocity is observed to increase slightly with the decrease of the tunnel radius with an increase by 7% at a radius of 400 m compared to a straight tunnel fire.

There are three regimes of the back-layering length for tunnel transverse fires. The first is for a fire next to the tunnel wall, where the back-layering length increases slowly initially followed by a rapid rise as the air speed tends to be lower than the critical velocity. Secondly, as a fire in the lane near the wall, the back-layering length increases at a gentle gradient with the decrease of the air speed. The back-layering length is smallest during these cases. A middle fire and a fire in the lane near the convex wall are considered as regime 3. The back-layering length evolution is steepest. In addition, the back-layering length increases significantly with the decrease of tunnel curve radius at the same air speed. In order to meet the firefighting, tunnel ventilation is needed for promising the smoke back-layering length less than 20 m and accordingly the air speed could be slightly lower than the critical velocity at next wall fires.

This maximum smoke temperature rise on the top wall for fires near the convex wall is slightly greater than for fires near the concave wall, and significantly higher than a middle fire in curved tunnels. A smaller curve radius of the tunnel also results in a higher maximum temperature rise, and accordingly a greater buoyancy. The air speed distribution is subsequently employed to explain the likely cause. The air speed near the convex wall is significantly lower than that near the concave wall, and decreases with decreasing the curve radius. Consequently, The lower surrounding air speed will diminish the heat convection of the fire plume, and the following increase of the smoke temperature rise. Besides, the local ventilation inertial is reduced as well. As a result, the tunnel ventilation speed has to be improved to suppress the smoke back-layer and stronger buoyancy for fires near convex wall in curved tunnels.

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