Study on the Influence of the Slope Composition of the V-shaped Tunnel on the Smoke Exhaust Efficiency of the Point Exhaust System

Fei Xie[1], *Junmei* Li[2*] ,*Wenbo* Liu[2], *Qiwei* Dong[1], *Cheng* Hu[3], *Zhao* Qi[2]

[1] Beijing General Municipal Engineering Design & Research Institute, Beijing 100124, China

[2] Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing Uinversity of Technology, Beijing 100124, China

[3] Beijing Academy of Science and Technology, Lab of safety and emergency management, Beijing 100000, China

Abstract The influences of the slope composition on both sides of the variable slope point and the opening numbers of the exhaust vent on the smoke diffusion and the smoke and heat exhaust efficiency in V-shaped tunnel were investigated by the numerical method. The results showed that for the asymmetric V-shaped tunnel, increasing the number of exhaust vents on the large slope side can improve the smoke and heat exhaust efficiency, but control the smoke in a smaller rang is relatively difficult. The corresponding smoke exhaust vent opening strategy should be drawn up in accordance with the composition of the slope of the V-shaped tunnel and the goal of the smoke control system in practice.
Keywords: V-shaped tunnel; smoke exhaust; fire; smoke spread

1 Introduction

In recent years, building more urban underground roads has become one of the main measures to relieve the urban traffic pressure in some large cities in China. Urban underground roads are generally located in the central urban area. With the continuous development of underground space, newly built urban underground roads often need to pass through existing underground facilities such as utility tunnel, subways etc., the vertical structure of these underground roads is becoming more and more complex, and it is no longer a simple horizontal or single-slope tunnel, but a combination of different forms of V-shaped sections.

V-shaped tunnel can be divided into a symmetrical V-shaped tunnel and an asymmetric V-shaped tunnel. During a fire, the smoke diffusion basically spreads symmetrically to both sides of the grade change point in the symmetrical V-shaped tunnel. In an asymmetric V-shaped tunnel, due to the tunnel slope on both sides of the grade change point is different, and leading to the different stack effect, this will have a greater impact on the flow of smoke. When there is a large slope difference in both side tunnel, the smoke may spread completely along one side with a large slope. The influence of the slope composition on both sides of the V-shaped tunnel on the smoke flow and the effect of smoke control must be studed deeply.

Following the relative tunnel design guide in China, point smoke exhaust systems are usually adopted in case of fire in urban tunnels. Research on point smoke

extraction in tunnels is mainly carried out in horizontal and single-slope tunnels [1-6]. For V-shaped tunnels, the current research mainly focuses on the smoke free diffusion and longitudinal ventilation smoke control [7], there is a lack of relevant research on point smoke extraction system. With the continuous development of underground space, fully understand on the smoke flow and smoke control in V-shaped tunnel is much more necessary. Based on this, The effects of the slope composition on both sides of the asymmetric V-shaped tunnel on the efficiency of the point smoke exhaust system would be studied, and the influence of different opening strategies of the exhaust vent on smoke control would also be investugated.

2 Numerical studies

2.1 Physical model

FDS (6.0) developed by NIST would be be used for the simulation in this paper. FDS is a field model, or known as application of Computational Fluid Dynamics (CFD). The transient conservation equations of mass, momentum, energy, and species for low-speed motion of a gas are solved numerically. Verification works on applying this FDS to simulate fire induced smoke transportation and dispersion were reported [8]. The predicted results agreed satisfactorily with the experiments, giving justification and confidence for application of FDS in this study.

The simulated tunnel is 13m wide and 6.5m high. A calpboard with the same width of the tunnel was

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* *corresponding author: lijunmei@bjut.edu.cn

installed under 2.0m of the celing, which consisted a smoke exhaust duct, and its thckness is 0.2m. The schematic diagrams of the simulated tunnel and its cross-section are shown in Fig. 1 and Fig. 2 respectively. The lengths of the tunnel on both sides of the V-shaped tunnel are 400m respectively. Any slope combinations of 1%, 3% and 5% are taken in the simulation, and the design fire power is 50MW. The fire is assumed to be located at the grade change point, and the simulated fire source is a surface with a length of 5m, width of 3m and height of 1m above the ground. The designed smoke exhaust rate is 200m³/s, and the size of a single exhaust vent is 3m × 2.5m, the distance between the exhaust vent is 60m. The arrangement of the exhaust vent is shown in Fig 3. When a fire occurs, three vents located at the upstream and downstream of the fire source respectively would be open to exhaust the smoke.
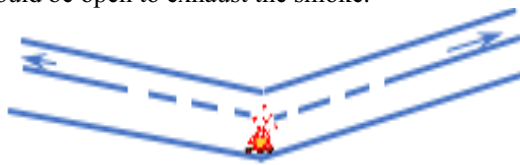

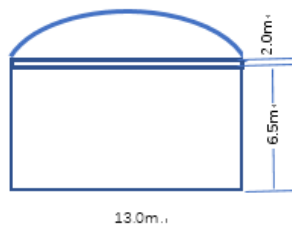**Fig. 1** The sketch of the V-shape tunnel

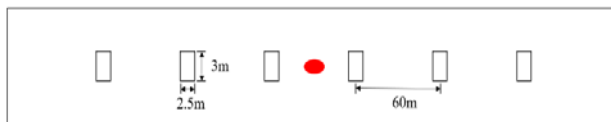**Fig. 2** The sketch of the cross section of the simulated tunnel

Fig. 3 The sketch of the exhaust vents location

2.2 Mesh size and simulation scenarios

Following the FDS user's guide[8], the grid size is set to be 0.5m × 0.5m × 0.5m, and within 100m on both sides of the fire source, the mesh is refined, and the grid size is 0.25m × 0.25m × 0.25m.

The detailed settings of the simulation scenarios are shown in Table 1. Smoke spread and smoke exhaust conditions are considered. In exhaust scenarios, the effects of the numbers of the vent opened on both sides of the fire source would be investigated. The ambient temperature is set as 20ºC, and tunnel wall and ceiling are taken as adiabatic in the simulations.

Table 1. Numerical scenarios

Test no	V-shaped section slope composition		Number of vent opening	
	small slope	large slope	small slope	large slope
KS01	1%	3%	0	0
KS02	3%	5%		
KS03	1%	5%		
PY04	1%	3%	3	3
PY05			2	4

PY06			3	3
PY07	3%	5%	2	4
PY08			1	5
PY09			3	3
PY10	1%	5%	2	4
PY11			1	5

3 Results and discussion

3.1 Smoke spreading distance

Fig. 4 gives the variation of smoke spreading distance with time under the free diffusion different smoke vent opening strategies on both sides of the fire source. It can be seen that at the beginning of the fire, smoke spreads symmetrically on both sides of the grade change point, and as the fire continues, the stack effect on the large slope side gradually increases, and the smoke on the small slope side will recirculation towards the fire source after spreading to a certain distance. When the slope of one side is large enough, such as 5%, after 400s, the small slope side is completely smoke-free, and the diffusion of smoke in the V-shaped section can be regarded as the flow in the single-slope tunnel. When the exhaust system is operated, the smoke extraction has a certain effect on the control of smoke, slowing down the smoke spread, but it is not good enough to control the smoke in a relatively small range, and the spread distance on the large slope side is more than 400m.

For the same exhaust opening method, the greater the difference in slope between the two sides of the grade change point, the better the effect of smoke control on the small slope side.
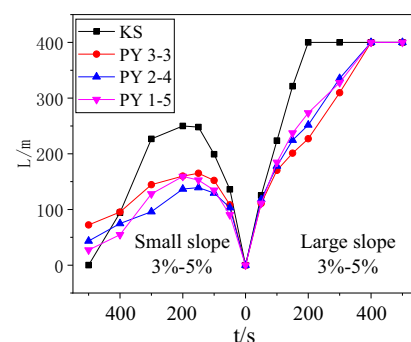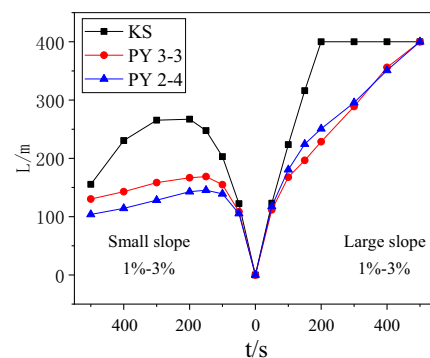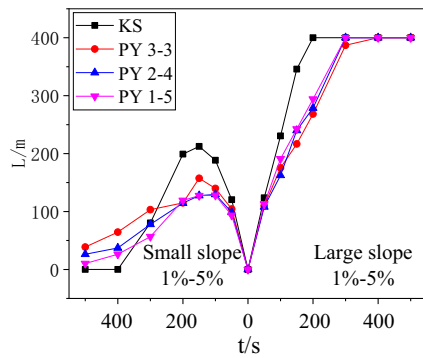
Fig. 4 Variation of the smoke spreading distance under different exhaust vents opening strategies in asymmetric V-shaped tunnel

3.2 Smoke and heat exhaust efficiency

The smoke and heat exhaust efficiency under different smoke exhaust opening strategies on both sides of the fire source are shown in Table 2. The smoke exhaust efficiency η_1 is defined as the ratio of the smoke exhaust rate of a vent $V_{e,vent}$ to the total amount of the smoke generated from the fire per unit time V_p. It can be expressed as

$$\eta_1 = \frac{V_{e,vent}}{V_p} \times 100\% \qquad (1)$$

The heat exhaust efficiency η_2 is the ratio of the heat exhausted through the exhaust vent Q_e to the heat release from the fire source Q. It can be calculated by

$$\eta_2 = \frac{Q_e}{Q} \times 100\% \qquad (2)$$

It can be seen from the table that the smoke and heat exhaust efficiency of each vent is not same under different opening strategies, and the smoke and heat exhaust efficiency of the left vent on the small slope side is lower. For the same slope combination, more exhaust vents opening on the large slope side, the smoke and heat removal efficiency would be a little higher. When the slope difference between the two sides of the grade change point is large, such as 1%-5% combination, asymmetricly opening the smoke vents on both sides of the fire source can improve the smoke exhaust efficiency effectively. However, when the slope difference is small, opening the exhaust vents like this has limit effect to improve smoke and heat exhaust efficiency.

Table 2. Smoke exhaust efficiency η_1 and heat exhaust efficiency η_2 under different exhaust vents opening strategies

Slope composition	Open strategy	Efficiency parameters	L3	L2	L1	R1	R2	R3	Total efficiency / %
1%-3%	3-3	η_1 / %	1.8	14.7	20.9	26.8	16.8	17.2	98.2
		η_2 / %	0.0	3.8	3.6	12.8	5.8	4.3	30.3
			L2	L1	R1	R2	R3	R4	
1%-3%	2-4	η_1 / %	7.8	24.5	27.2	12.7	12.7	14.6	99.5
		η_2 / %	3.0	3.9	13.3	6.1	5.3	3.2	34.8
			L3	L2	L1	R1	R2	R3	
3%-5%	3-3	η_1 / %	2.5	1.8	11.8	25.0	14.1	17.7	72.9
		η_2 / %	0.0	0.0	4.6	15.0	7.8	7.2	34.6
			L2	L1	R1	R2	R3	R4	
3%-5%	2-4	η_1 / %	2.3	1.8	21.8	16.3	15.0	17.7	74.9
		η_2 / %	0.0	2.8	15.9	6.1	4.5	5.8	35.1
			L1	R1	R2	R3	R4	R5	
3%-5%	1-5	η_1 / %	4.8	24.5	11.8	10.9	9.7	14.0	75.7
		η_2 / %	0.2	20.4	6.8	2.6	3.3	4.0	37.3
			L3	L2	L1	R1	R2	R3	
1%-5%	3-3	η_1 / %	0.0	0.0	1.8	25.4	18.6	22.7	68.5
		η_2 / %	0.0	0.0	0.1	14.7	6.4	6.9	28.1
			L2	L1	R1	R2	R3	R4	
1%-5%	2-4	η_1 / %	1.4	1.8	29.0	18.1	13.3	16.0	79.6
		η_2 / %	0.0	0.0	15.2	7.3	5.3	6.0	33.8
			L1	R1	R2	R3	R4	R5	

| 1%-5% | 1-5 | η_1 / % | 1.8 | 32.7 | 15.4 | 6.8 | 9.1 | 14.8 | 80.6 |
| | | η_2 / % | 0.0 | 18.5 | 6.9 | 2.6 | 3.2 | 4.4 | 35.6 |

4 Conclusions

For a given HRR and fire location, the slope composition on both sides of the slope change point in the V-shaped tunnel has a great effect on the smoke spread and smoke control effect of the exhaust system. The influence of the above factors were discussed by numerical method, the following conclusion were drawn:

(1) For the large slope differences on the both side of the fire source, the smoke on the small slope side will backflow, the smoke will spread to the large slope side. When the large slope is 5% and the fire lasts more than 400 s, the small slope side is basically smoke-free and the smoke spread in the V-shaped section can be regarded as smoke flow in a single-slope tunnel.

(2) For the point smoke extraction, if the number of smoke exhaust vents on both sides of the fire source was opened asymmetrically, more smoke exhaust vents on the large slope side opened can improve the total smoke and heat exhaust efficiency, but it is difficult to control the smoke in a small range. The corresponding smoke exhaust vents opening strategy should be drawn in combination with the composition of the slope of the V-shaped tunnel and the overall goal of smoke control in practical engineering.

Acknowledgement

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