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Influence of fire source locations on fire spreading characteristics in slope tunnel

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Abstract. To explore the influence of fire source locations on temperature distribution characteristics and smoke spread in certain slope tunnel, CAD software was used to model a 2% constant slope tunnel and pre-arranged temperature measuring devices. Temperature measuring devices on slope tunnel were reasonably arranged. Fire source powers were controlled by rotor flowmeter. In the absence of wind, experiments of locations liquefied petroleum gas with power of 0.125, 0.25 and 0.375 were carried out on different fire source positions. Meanwhile, slope level control group was set. The results show that temperature peak occurs at ±40 cm distance from the tunnel center with the accumulation of smoke. Bottom peak is higher than top peak, however, the level range of high temperature region is larger than top area. With fire power and slope increase, flue gas temperature increased and flue gas influence of top tunnel is expansion, while temperature influence on bottom becomes less.

Keywords: slope tunnel, fire source locations, fire spreading, smoke accumulation.

1. Introduction

In recent years, China has become one of the fastest growing construction markets on tunnel and underground engineering. Tunnel construction technology reaches advanced level in world. With tunnel types increased, tunnel fire safety has attracted more attention. As the narrow space characteristics of tunnel, smoke is hard to discharge in fire event, high temperature and burning toxic gases are serious threats to people life and property safety, with the immeasurable losses of severe construction damage of tunnel structure. G15 Shenhai high-speed Maoliling tunnel fire [1] on August 27, 2019, fire was put out in 5 minutes and failed, smoke spread rapidly and more than 80 vehicles and people were stranded in the tunnel. The accident caused 5 persons death, 31 injuries, and more than 5 million yuan economic losses. Shanxi Yanhou tunnel fire killed 40 persons, injured 12, burned 42 vehicles and caused direct economic losses of 81.97 million yuan in 2014. As the experience lack of effectively in slope tunnel fire escape and rescue, Austrian Alps ski cable-car [2] tunnel fire resulted in 155 people death, only 11 persons survive towards the end carriages fire escape under an experienced fireman guidance. Fire happened in sloping tunnels, flue gas was tilted upward spread and spread speed was far beyond the escape velocity people. Upward sloping tunnel escape was not desirable, without the basic safety facilities equipped of cable car and corresponding exhaust facilities of inclined tunnel, variety safety

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problems led to the tragedy happened. The most important was the lack knowledge and corresponding preventive measure of inclined tunnel fire safety and fire smoke spreading in inclined tunnel.

To provide the reality of vehicles in the inclined tunnel fire exhaust measures and escape methods, influence of fire source locations on fire spreading characteristics in slope tunnel is researched in this paper. At present, tunnel fire safety is still a hot field, numerical simulation and experimental research have been carried out in fire safety research. However, due to the particularity and complexity of tunnel fire, a large amount of data still needs to be obtained in experimental research. More accurate and practical software programs of tunnel fire and smoke accumulation are still needed to be obtained [3].

With the special construction structure of a certain slope, fire probability of inclined tunnel is much higher than no longitudinal slope tunnel. When a fire occurs, "Chimney effect" will change the flow state of smoke in the tunnel, which will lead an important influence on the distribution of fire tunnel temperature field and different characteristics of horizontal tunnel. Fire source height and fire source locations affect the fire smoke spreading in the tunnel. In this paper, influence of fire source locations on fire spreading characteristics in slope tunnel has been carried out, which has great significance to understand the rule of fire spreading and smoke accumulation and to take effective prevention and control measures to slope tunnel fire.

At present, researches about tunnel fire experiments are few, experimental phenomena and conclusions are still unclear. In this paper, small size tunnel experiment platform (1:20) with gas ignition and oil basin was used to carry out the experiment. Oil brazier was used to igniting, and gas fire source power was changed by rotor flow meter to research the influence of fire source size on flue gas and temperature of tunnel at different locations. Liquefied petroleum gas (LPG) with main components of propane and butane was used as gas ignition source [4]. In order to be applicable in practice, heat release rate generated by different vehicles on fire at a 2% slope were used to conduct the experiment [5]. Heat release rate of different vehicles on fire was shown in Table 1. Fire source locations under the influence of chimney effect [6] and slope will provide important practical significance for realistic tunnel fire analysis and prevention. After the 2% slope tunnel test, fire experiment in horizontal tunnel was carried out. Chimney effect influencing on smoke and temperature spread was comparatively analyzed by control variable method in slope tunnel fire, influence of slope was studied and analyzed as the same time.

Table 1. Heat release rates of different vehicles on fire.

Vehicle type	Car	Van	Truck or bus	Car tank lorry	Large gasoline tanker
HRR (MW)	3-5	10	20	50	100

2. Experiments

According to similarity theorem, a small size tunnel experimental tunnel (1:20) with 600 cm length, 50.2 cm width and 30.60 cm height was applied in the experiment (Fig. 1). Fire source was composed of LPG and a brazier (20 cm × 20 cm × 10 cm). Fire source powers were changed by the LPG rotor flow meter (range 0.125 - 5 N/m^{3}h). Fire source positions were changed by the brazier positions. LPG is divided into propane and butane and has calorific value of 45500 kJ/kg. Combustion efficiency is 0.7 in this experiment. Table 2 shows the properties of propane and butane according with SFPE [6]. Fig. 2 is the photos of gas tank, rotor flow meter and brazier.

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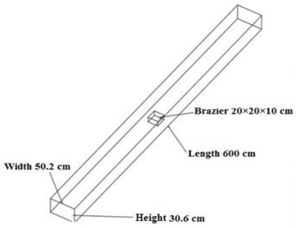

a) Diagrammatic drawing.

b) Real products picture.

Figure 1. Small size tunnel experimental tunnel (1:20).

Table 2. Combustion heat of propane and butane.

Properties	Propane	Butane
Molecular formula	C_3H_8	C_4H_{10}
Molecular weight	44.09	58.12
Density (kg/m^3)	1.83	0.584
Combustion heat (MJ/kg)	46.36	45.7
Autoignition temperature (T)	450	430.6

a) Gas tank and rotor flow meter.

b) Brazier.

Figure 2. Gas tank, rotor flow meter and brazier.

Calculation formula of fire source power is as Eq. (1):

$$P = 0.7 \times \Delta H \times \rho \times V \div 3600 \quad (1)$$

P is power, ΔH is LPG calorific, ρ is density of LPG gas, ΔH = 45500 kJ/kg, ρ = 2.35 kg/m^3.

Thermocouples distribution setting is based on the temperature flue gas theory. Heat conduction and thermal radiation effect can be ignored when the tunnel has a certain distance from fire source. Temperature measured by thermocouple can be approximately regarded as the temperature and distribution of flue gas. All the thermocouples used in this experiment are K-type thermocouples, composed of nickel-chrome and nickel-aluminum bimetal. Temperature measurement range is 0 - 1300 ^{o}C. Thermocouples distribution is adopted the following strategies after several discussions and calculations. The whole tunnel is into divided four areas, including top, upper, lower, and bottom following the slope. Data collectors are assigned in each area with same time. Data record interval is 1 s. A total of 49 thermocouples were used in this experiment. Thermocouples profile of distribution and configuration is shown in Fig. 3.

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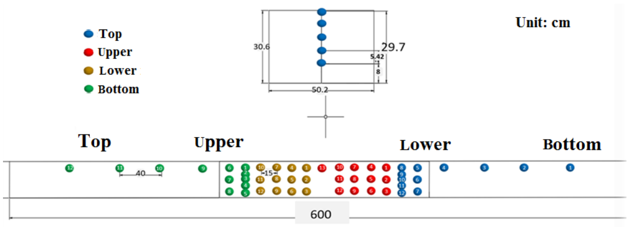


Figure 3. Thermocouples profile of distribution and configuration.

As shown in Fig. 3, thermocouples number varies at each location. The most intensive thermocouple horizontal setting is the middle part of tunnel and the thermal horizontal distance between adjacent thermocouples is 15 cm. Thermocouples is sparsely in the top and bottom of tunnel, and the horizontal distance is 40 cm. The horizontal setting can clearly observe the temperature spread around fire source. Thermocouples are sparse far from fire source with less temperature gap. More useful data will be obtained by the reasonable thermocouples arrangement. In the middle and upper reaches of the region, there are three thermocouples in the upper and lower areas, and one thermocouple in the top and bottom areas. Multiple thermocouples at the ignition point can effectively observe the center temperature changes and smoke spreads around brazier during burning. Flue gas spread to top and bottom are ceiling spread flue gas. One thermocouple is enough to judge the flue gas spread rule by temperature observing.

The most special setting is the five thermocouples with different heights closed to tunnel center. They are used to observe temperature rise by the through smoke at the five heights, which can judge the smoke spread path. Thermocouples heights are derived from the height of people and tunnel ceiling under the same proportion. One thermocouple height is ceiling height. Three thermocouples height are the same proportion of human height, the average of human height and ceiling height, and the ceiling height from low to high. Five thermocouples height are converted by the equal proportion of three thermocouples heights. In this way, thermocouples of different heights are set up to obtain the change of height gradient caused by smoke spread.

Three conditions were set and data recording under no wind (0 m/s) and 18 ^{o}C constant room temperature (Table 3).

First group, 2% slope, brazier positions and heights unchanged (10 cm), and the fire source powers were changed with 2, 5 and 7.5 kW.

Second group, fire source powers unchanged (2.5 kW), brazier positions and heights unchanged (10 cm), tunnels slope levels were changed 0, 2% and 5%.

Third group, 2% slope, fire source powers unchanged (1 kW), fire heights were changed by the brazier height of 10, 15 and 20 cm.

Table 3. Experiment conditions.

Working condition	Source power	Slope	Ignition point height
First group	2.5	2	10
	5	2	10
	7.5	2	10
Second group	2.5	0	10
	2.5	2	10
	2.5	5	10
Third group	1	2	10
	1	2	15
	1	2	20

3. Results and analysis

Pre-experiment had been carried out to determine the combustion time through thermocouples temperature (Fig. 4). LPG had been burning under the condition that fire source set in the middle of tunnel, fire source power was random and slope was 2%. A plot analysis about recording data showed that thermocouple temperature tended to be stable between 300 and 350 s after flame ignited, which finally deciding the burning time as 330 s. Thermocouples temperature variations after 330 s would remain basically constant in subsequent tests.

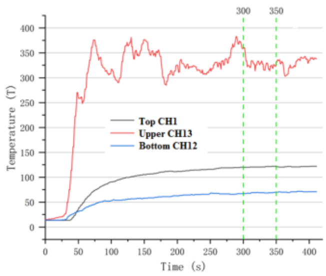
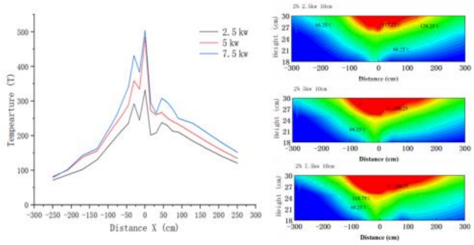


Figure 4. Thermocouples temperature and time curves in pre-experiment.

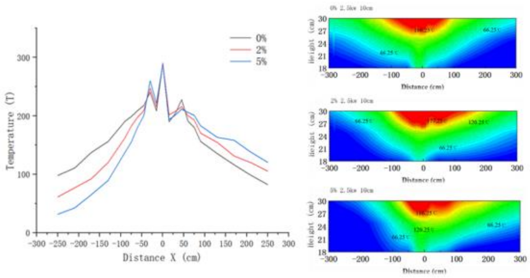
Fig. 5a shows the temperature distribution diagram of tunnel ceiling below at 2% slope, 10 cm fire source height, 2.5, 5 and 7.5 kW fire sources powers. Fire source with the higher power get a higher temperature in tunnel. The peak values appear at -40 cm and 40 cm away from the tunnel, which are caused by smoke accumulation. Fig. 5b shows the temperature distribution cloud diagram in the top and upper areas of tunnel with different fire sources power. It can be seen that larger fire power led a wider temperature distribution in whole tunnel.



a) Temperature distribution. b) Temperature distribution cloud.

Figure 5. Temperature distribution diagram of first group.

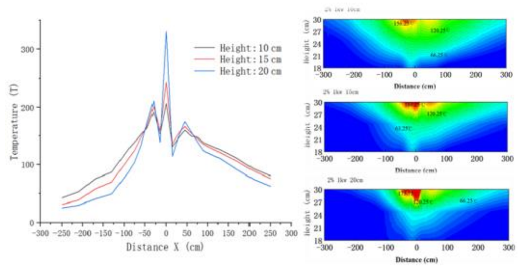
Fig. 6a shows the temperature distribution diagram of tunnel ceiling below at 2.5 kW fire source power, 10 cm fire source height, 0%, 2% and 5% slop. Peaks value appear at -40 cm and 40 cm away from the tunnel, which are caused by smoke accumulation too. With The fire source with higher power get a higher temperature in tunnel. With the increase of slope, the temperature gradient of bottom tunnel get larger, and the top tunnel become smaller. Fig. 6b shows the temperature distribution cloud diagram in the top and upper areas of tunnel with different slope. It can be seen that larger slope led a wider temperature distribution in top tunnel, but a narrower temperature distribution in bottom tunnel.



a) Temperature distribution.   b) Temperature distribution cloud.

Figure 6. Temperature distribution diagram of second group.

Fig. 7a shows the temperature distribution diagram of tunnel ceiling below at 2% slope, 1 kW fire source power, 10, 15 and 20 cm fire sources height. It can be seen that with the increase of fire sources height, temperature get larger on coverage area of up tunnel, while that of bottom tunnel get smaller. Fig. 7b shows the temperature distribution cloud diagram in the top and upper areas of tunnel with different fire sources height. As the fire source height rises, tunnel roof temperature get higher on fire location, temperature distribution get narrower at up and bottom tunnel, corresponding less influence under the tunnel.



a) Temperature distribution.   b) Temperature distribution cloud.

Figure 7. Temperature distribution diagram of third group.

4. Conclusions

Four conclusions have been gotten by the dated analyzed as following: i) Smoke accumulation areas are appeared at -40 cm and 40 cm tunnel roof away from the fire source, which resulting in temperature peaks. Temperature peak of flue gas accumulation in bottom area is larger than that in up area, but up high temperature area transmits farther horizontally; ii) As the fire source power increases, temperature distribution of whole tunnel is increasing; iii) As the tunnel slope increases, flue gas tend to move up, temperature impact on bottom get less; iv) As the height of ignition point increases, smoke is concentrated in the tunnel ceiling area, less influence works on the tunnel below.

Tunnel is an important key lines and traffic node. Be used appropriate, the conclusions, such as installing water curtain or fire protection equipment at the ±40 cm positions in equal proportion, can prevent the fire occurrence or spread, reduce the fire incidence of highway and the losses of personnel casualties and property. It is shown that the frequency of road tunnel fire is 2 times per 100 million vehicle kilometers with huge loss. More than 300 people were killed and 270 injured in a deadly subway tunnel fire in Baku, Azerbaijan, which would have been reduced if this experiment is successfully applied to highway tunnel and railway tunnel. It is urgent for the real world with increasing number of tunnels.

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