Full Scale Experiments on Studying Smoke Spread in a Road Tunnel

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ABSTRACT

Three full scale tests were conducted in a road tunnel to study the smoke spread with different fire sizes and wind speed conditions. The smoke temperature under the ceiling, the smoke layer height distribution and the travel of the smoke front in a 1000 m long domain along the road tunnel were measured. Results showed that wind speed had much influence on the spread of smoke in the tunnel. When wind speed was such low as less than 1 m/s, a smoke layer could form and stabilize all along the tunnel. But when the wind speed was such high as more than 2 m/s, smoke layer could only be maintained in a distance of about 400 m in the downstream. The slowdown of the traveling of the smoke front in the downstream along the tunnel was more obvious when the wind speed was smaller. All these full scale data presented here can be used for further study on the verification or improvement of existing fire models for enhancing their applicability to such long tunnels.

KEYWORDS: full scale experiments, road tunnel, smoke spread, wind speed

INTRODUCTION

In recent years, fires occurred underground brought about catastrophic results, such as the arson fire in a subway tunnel in Daegu Korea on February 18, 2003, killing 198 people [1], two other arson fires in Hong Kong and Russia, and the fire under an old escalator at King's Cross underground station in London, killing 31 people and causing extensive damages [2]. More and more attention is being paid to the fire protection of long underground tunnels. Investigations showed that smoke was the major fatal factor in such fires, especially in tunnel fires where much toxic gases were released due to incomplete combustion [3,4]. So, smoke control is very important for saving lives in case of underground tunnel fires [5]. In order to provide appropriate fire protection, the physics of fire growth and smoke spreading in a tunnel should be well understood for the first [6,7].

Many bench scale tests have been performed to study the fire characteristics, smoke movement and control in case of a tunnel fire [8,9]. Numerical simulations have also been tried to predict the fire development and to investigate into the efficiency of different smoke control methods in tunnels [10,11]. Functional relationships have been derived from laboratory scale tests [8,9,13]. All the numerical simulation results and the functional relationships should be validated, especially by full scale data.

Some full scale tests have also been carried out in the past years [13]: In 1992, large scale tests were carried out in a disused two-lane highway tunnel in Virginia, USA with length of 850 m and longitudinal slope of 3.2%, to assess the heat output. Afterward, an

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extensive series of experiments were conducted at HSL, Buxton in a 366 m long, 2.56 m high tunnel with a cross-section of 5.4 m^2, to provide data suitable for the validation of CFD simulation. In 1994, tests were performed in a disused Norwegian mine tunnel, nominally 5.5 m high, 6.5 m wide and 2.3 km in length under the EUREKA EU499 project [12]. The main objective of this series of tests was to determine the heat output of fire in tunnels and the velocity profile upstream of the fire.

All of these full scale tests have provided very useful data, but still with some limitation: Most of them were conducted in spaces with limited dimensions, while the real scale of a road tunnel should be up to 7 m high and 8 m wide. In EUREKA EU499 tests, the walls were also rough and the cross-sectional area was significantly different with location unfortunately [13]. Although the tunnel size for the tests in Virginia was 7.9 m high and 8.8 m wide, the length of the tunnel was only 850 m while it would be desirable to get the full scale data in a tunnel as long as 1500 m. And the region for data measurement was also limited: In the HSL tests and the UREKA EU499 tests, data were only collected from 50 m upstream to 200 downstream [13] and from 100 m upstream to 100 m downstream [12] along the tunnel, respectively. It is considered to be useful to get the full scale data farther away from the fire.

In this paper, full scale data, on the smoke temperature under the ceiling, the smoke layer distribution and the travel time of the smoke front, were collected within about 200 m upstream and 800 m downstream region (the directions of 'upstream' and 'downstream' were defined in reference to the direction of longitudinal ventilation as shown in Fig. 1) in a 2725 m long road tunnel under different longitudinal wind speeds.

EXPERIMENTAL PROCEDURE

The Road Tunnel for Test

Full scale tests were conducted in the *Yangzong Road Tunnel*, belonging to the highway connecting Kunming and Shiling in Yunnan province, China. The plan view of this tunnel is shown in Fig. 1.

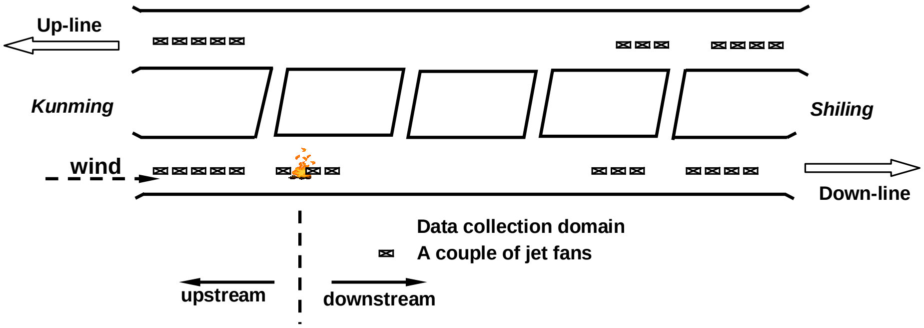


Fig. 1. Plan view of the *Yangzong Road Tunnel* (not to scale).

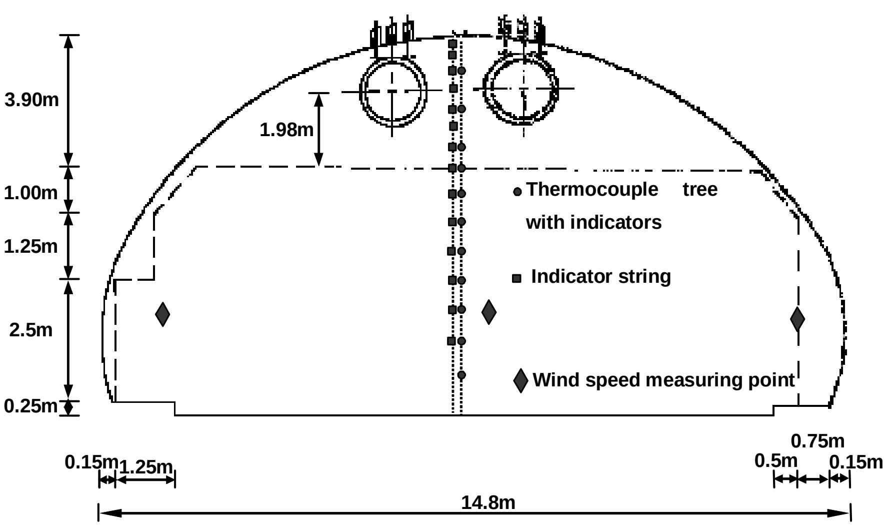


Fig. 2. Cross-sectional view of the *Yangzong Road Tunnel* (not to scale).

The *Yangzong Road Tunnel* consists of a down-line tunnel leading from Kunming to Shiling and an up-line tunnel in the opposite direction. Both of the tunnels are unidirectional with three lanes each. The lengths of the down-line and the up-line tunnel are 2725 m and 2790 m with longitudinal slopes of 1.09% and 1.15% all along respectively. The cross sections of the two tunnels are the same as that shown in Fig. 2, with width of 14.8 m and height of 8.9 m. There are four cross cavities connecting these two tunnels, which were designed for human to evacuate to the other tunnel when fire occurs in one of them. Both tunnels are mainly straight at the middle part. The down-line tunnel, which have more long straight way up to 2500 m and only a very short curve near the entrance, was selected for the tests. Longitudinal ventilation systems are designed for the tunnels: Jet fans with four levels of flux are installed for air ventilation and smoke exhaust. The properties of the jet fan are Diameter=1.25 m, outlet velocity of about 30.3 m/s, volume flux of about 37.1 m^3/s. There are 30 such jet fans installed in the down-line and 24 for the up-line. The locations of the jet fans are also shown in Fig. 1.

Experimental Setup

Pool fires were positioned at 700 m into the down-line tunnel as fire sources. The designs of the pool fires are as shown in Table 1.

Table 1. Set up of fire sources.

Test No.	Pool size	Fuel	Burning time	Heat Release Rate
1	One square pool of size 1 m × 1 m	Gasoline, 20 liter	7 minutes	1.4 ~ 1.6 MW
2	Two square pool of size 1 m × 1 m	Gasoline, 30 liter for each pool	6 minutes and 20 seconds[a]	3.2 ~ 3.7 MW
3	Two square pool of size 1 m × 1 m	Gasoline 9 liter with Diesel 10 liter for each pool	15 minutes	2.5 ~ 2.8 MW

[a] Being put off when still burning.

The heat release rates of the pool fires were estimated by the mass loss rates measured, the combustion efficiency, which were taken to be 70% ~ 80% for pool fires commonly, as it is still unknown how large it accurately should be in tunnels, and the heat of combustion of gasoline and diesel, which were taken to be about 45,000 kJ/kg and 42,000 kJ/kg, respectively.

Three quantities on smoke spread were mainly measured, smoke temperature under the ceiling, vertical smoke temperature at certain positions and horizontal traveling time of smoke front along the tunnel. The horizontal distribution of smoke temperature under the ceiling was acquired by thermal resistors positioned at 0.3 m below the top of the ceiling. These thermal resistors were positioned at 20 m intervals from +20 m to +800 m. The vertical smoke temperatures were measured at certain positions at -20 m, +20 m, +200 m, +400 m, +600 m and +800 m from the fire by thermocouple trees as seen in Fig. 2. For every thermocouple tree, 11 thermocouples were positioned at 7.5 m, 6.5 m, 5.5 m, 5.0 m, 4.5 m, 4.0 m, 3.5 m, 3.0 m, 2.5 m, 2.0 m and 1.0 m respectively. The errors of temperatures measured by the thermal resistors were estimated to be ± 0.5^{o}C, while it to be ± 1 or 3% for the thermocouples, respectively. The times taken for horizontal smoke front to travel downstream were recorded visually by an observer for intervals of 25 m from +25 m to +725 m and another observer to record the time taken to travel upstream.

Smoke layer interface heights were also tried to be visually recorded by eye sight. For every thermocouple tree, there were indicators at the same positions as that of the thermocouples. And also, there were two indicator strings positioned at +100 m and +300 m. For these indicator strings, indicators were positioned vertically at 15 positions from height of 8.5 m to 1.5 m with intervals of 0.5 m. All the indicators were made by different colored bands to be easier to distinguish.

All these thermocouples trees and indicator strings were positioned at the central longitudinal plane of the tunnel as shown in Fig. 3.

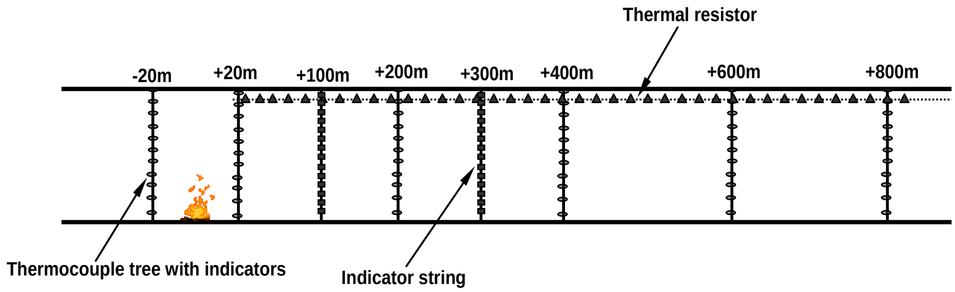


Fig. 3. Longitudinal schematic cross-section of the measuring domain.

Three kinds of wind conditions were designed for the three tests respectively:

Test1: Longitudinal ventilation system was operated before ignition with a normal ventilation rate of about 280 m^3/s;

Test2: Jet fans were all shut down, but still with low natural wind speed;

Test3: Longitudinal ventilation system was activated at the fire smoke ventilation rate of about 540 m^3/s, when fire detection system had detected the fire.

As also shown in Fig. 2, for every test, wind speeds were measured at three cross sections which were at the fire source, +200 m and +400 m. For each cross section, wind speeds were measured at three typical positions A, B and C as shown in Fig. 2, which were at about 2 m high from the floor level. The wind speeds were measured by a wire anemometer from 3 minutes on after ignition when the measured values were shown to be fairly steady.

RESULTS AND DISCUSSION

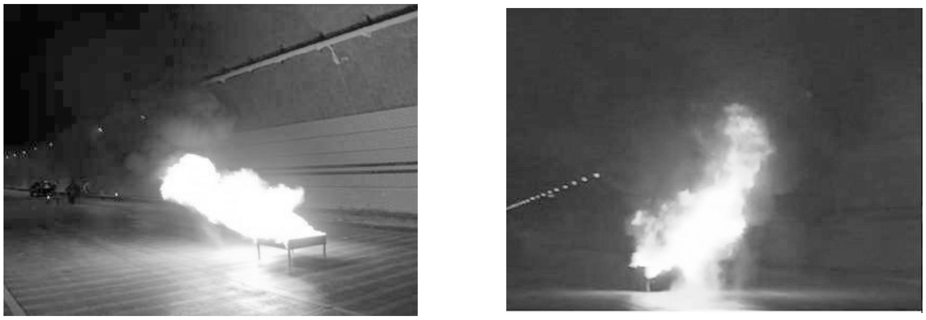
Wind Speed Conditions

The wind speeds measured for each of the three tests are shown in Table 2. It can be seen that the velocity was much larger near the fire source than at positions downstream at +200 m and +400 m for Test 2 when the jet fans were all shut down. While in Test 1 and Test 3, when the jet fans were operated, the wind speeds seemed to vary little in the 400 m region downstream. The larger velocity profile near the fire source in Test 2 is considered to be related to the air entrainment by the fire. There may be turbulent velocity near the fire source and it would be become "fully developed" only at an infinite distance downstream as pointed earlier in the former report in other full scale tests [12]. So, the wind speeds measured downstream is considered to actually represent the wind conditions in the tunnel.

And it was also observed that the wind speeds influenced much on the fire flame and plume shape. When wind speed was large, the flame tilted largely and the smoke plume was blown towards downstream before it reaches the top of the ceiling, as can be seen from Fig. 4a. When wind speed was larger than 4 m/s, the flame was even pressed down to near the ground level as can be seen in Fig. 4d.

Table 2. Wind speed data measured (m/s).

Test No.	**Measuring position (refer to Fig. 2 and Fig. 3)**							
	Fire source		**+200 m**			**+400 m**		
	A	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	2.1	3.0	2.5	2.5	3.0	2.8	2.5	2.3
2	2.5	3.0	0.8	0.8	0.6	0.3	0.2	0.3
3	3.4	4.7	4.7	5.1	4.7	/	/	/



(a) test1, photo from upstream

(b) test2, photo from downstream

(c) test3, photo from downstream, before jet fan operation

(d) test3, photo from downstream, after jet fan operation

Fig. 4. Typical photos indicating influence of wind speed on the fire flame and plume.

Longitudinal Smoke Temperature below the Ceiling

The maximum smoke temperatures measured below the ceiling by the thermal resistors are plotted against the distance downstream from the fire source in Fig. 5. It can be seen that the smoke temperature decayed fast when traveling down the road tunnel. The maximum temperature rises below the ceiling measured at +20 m were 14, 43.5, and 24 for Test 1, Test 2 and Test 3 respectively. But after traveling about 700 m downstream, they were all near to the ambient temperature. The decay of smoke temperature is considered to be mainly due to the convective heat loss to the surrounding wall surface, the radiative heat loss to the boundaries and the mixing of the ambient air be seen that the smoke temperature decayed fast when traveling down the road tunnel. The maximum temperature rises below the ceiling measured at +20 m were 14, 43.5, and 24 for Test 1, Test 2 and Test 3 respectively. But after traveling about 700 m downstream, they were all near to the ambient temperature. The decay of smoke temperature is considered to be mainly due to the convective heat loss to the surrounding wall surface, the radiative heat loss to the boundaries and the mixing of the ambient air.

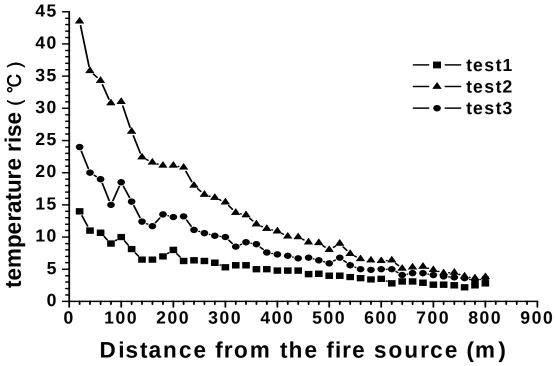
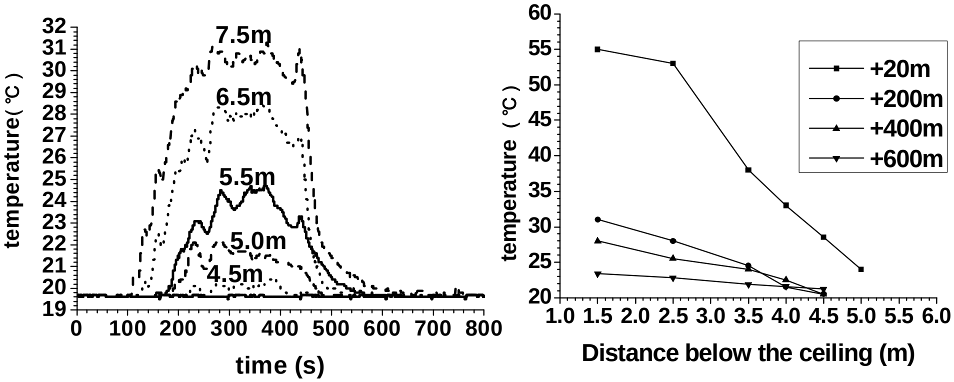


Fig. 5. Temperature rise measured
at 30cm below the ceiling.

Smoke Layer

In Test 1, smoke layer was seen to maintain stratification up to a certain distance downstream and as the wind speed was relatively large, no back layering phenomenon was seen. In Test 2, smoke layer was maintained all along the tunnel till it spilled out. Back layering occurred with a distance of about 200 m upstream from the fire during the burning time. And in Test 3, smoke layer first maintained stratification and back layering phenomenon also occurred, as can be seen from Fig. 4c. But at about 300s after ignition, when the jet fans were operated, the smoke layer mixed with the air below, the interface disappeared soon and the upstream moving of the back layering stopped at about 90 m upstream from the fire.

In order to investigate how smoke layer developed along the tunnel, the smoke layer height was derived by two methods, i.e., by the vertical thermocouple data and by visual observation.



(a) Typical temperature data by
a thermocouple tree

(b) Vertical temperature profiles

Fig. 6. Smoke temperature measured by thermocouple trees (Test2).

A typical vertical temperature distribution measured is shown in Fig. 6a for Test 2, at +200 m). It can be seen that the temperature decayed fast as it went vertically down. In this example, the temperature measured by the thermocouple at 4.5 m high was slightly higher than the ambient temperature while the lower thermocouples demonstrated no temperature rise. The smoke/thermal layer heights were judged as the position of the lowest thermocouple that recorded temperature rise. For example, the smoke/thermal layer for Fig. 6a, at +200 m for Test 2 was 4.5 m. Typical vertical temperature distributions at different distances downstream the fire are also shown in Fig. 6b (data at +800 m was omitted due to the uncertainness of reaching a steady temperature state there). It can be seen that smoke temperatures decrease almost linearly with distance down from the ceiling except that at +20 m. For that at +20 m, the temperatures measured by the two uppermost thermocouples were close and much higher than those measured by the other four thermocouples, which also decay linearly.

The smoke/thermal layer distribution from vertical thermocouple tree and visual observation are shown in Fig. 7 (“square” and “triangle” indicate the smoke/thermal layer by thermocouple and the smoke layer visually observed, respectively) for the three tests. When smoke layer stratification disappeared and the smoke was seen to fill the entire cross section, the smoke layer height was deemed to be zero.

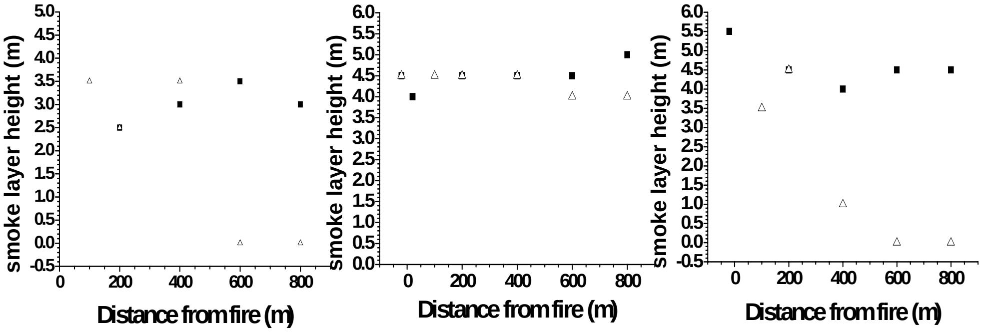


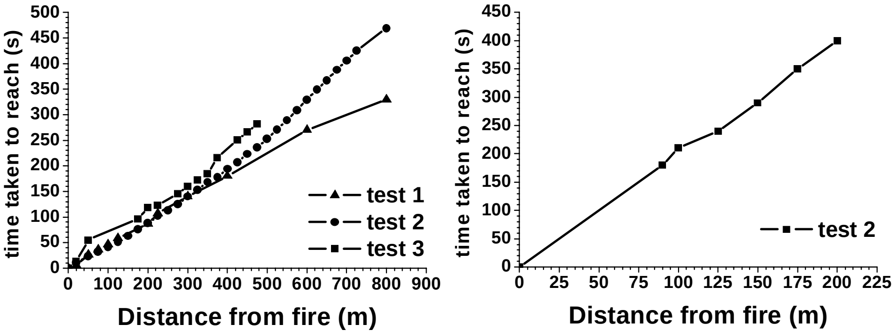
Fig. 7. Smoke layer distribution along the tunnel by
thermocouple tree and by observation.

It can be seen that the actual thermal layer height deduced by thermocouple data differed with that visually observed. In Test 1, in which jet fans were all shut down, this difference was relatively small and only existed at distance more than 400 m away from the fire. But when jet fans were operated, this difference was much large. And the larger the longitudinal wind speed, the larger the difference was, as can be seen that difference began to be considerable at +600 m for Test 1 and that at +400 m for Test 3.

It can be also seen that in the case of jet fans were all shut down in Test 2, smoke layer remained well stratified with fresh air below at the safe enough height, although descended some in the downstream according to the observed data. But when the jet fans were operated, smoke descended to ground level at some distance downstream. And the smoke descended to ground level at shorter distance downstream when larger wind speed was generated by jet fans at higher operation level.

Traveling Time of Smoke Front

The times taken for longitudinal smoke front to travel downstream in the tunnel are shown in Fig. 8a. It can be seen that more times taken at distance farer away from the fire after traveling 300 m in Test 2 with jet fans all shut down, indicating obviously a longitudinal smoke front velocity decay. But in Test 1 and Test 3, the traveling time seemed to be linearly increasing with the distance from the fire source. And the traveling time of back layering in Test 2 is also plotted with distance upstream the fire source in Fig. 8b. It can also be seen that the upstream longitudinal smoke front velocity was nearly constant. According to these data, the average velocity can thus be deduced according to the value of the slope by linear fitting of traveling time against the distance from the fire source. And the average velocity of the upstream smoke front in Test 3 was just according to the final distance traveled during ignition time. These are summarized in Table 3.



(a) downstream (b) upstream

Fig. 8. Traveling time recorded of longitudinal smoke front.

Table 3. Average longitudinal velocity of smoke front.

Test No.	**1**	**2**		**3**	
Direction	**downstream**	**upstream**	**downstream**	**upstream**	**downstream**
Velocity	2.3 m/s	0.5 m/s	1.9 m/s	0.3 m/s	1.8 m/s

It should be noted that the average velocity downstream for Test 3 should be considered as in case of with no jet fan operated. As the data on traveling times of longitudinal smoke front collected in this test were in 300 s after ignition, during which jet fans were not activated. After the jet fans were operated at the smoke extraction level, the smoke layer was mixed with air below and it was too disturbed to visually track its front. It can be seen that the traveling velocities of smoke front between upstream and downstream were so different even when the longitudinal wind speeds were small. This should due to the fact that the smoke front upstream would 'conflict' with the oppositely coming longitudinal wind, resulting in more air entrainment and temperature decrease. Both these two factors should lead to velocity decrease.

SUMMARY

Some full scale data on fire smoke spread in a road tunnel were collected and presented in this paper. Preliminary, it can be seen that the longitudinal wind speed influenced largely on the development of fire flame, fire plume and the spread of fire. When jet fans were all shut down with only environmental wind speed in the tunnel, smoke layer can be maintained at the upper space of the tunnel with well stratification with fresh air below. When jet fans operated, it blew the smoke at the upper space down to the ground level. The faster the wind speed was generated by the jet fans, the shorter the distance downstream from the fire where smoke layer can be maintained. So, it may be more practical to shut down all the jet fans at the early stage of a tunnel fire to maintain the stratification, and thus to provide the unpolluted environment below to cater for the human evacuation. Jet fans should be activated when human evacuation is completed and to play their efficient action on smoke control and ventilation to help the brigade to approach the fire for fire fighting.

The data on longitudinal smoke temperature and layer height distribution, the longitudinal traveling times of smoke fronts under different fire size and wind speeds can be further applied for verification of fire models and fire simulation tools in case of tunnel fire predictions. However, although some data were preliminarily gotten, some incompleteness still remained. The Heat Release Rates were not accurate enough, the wind speeds were only measured at some certain point and it was not capable to track the smoke layer height at far away from the fire, 400m away for example, by thermocouple. Oxygen consumption way calorimetry will be improved as in the former report [12] and introduced into the Heat Release Rate estimation in the future full scale tests. The pool fires should be burned longer enough to get the smoke temperature to reach a steady state at far away from the fire, for example, +800 m or farther. And infrared beams will also be tried to track the smoke layer position vertically, which had been used by us in the former tests in a full scale underground corridor [14]. All of these works including model verification and further better equipped tests above will be done in the future.

ACKNOWLEDGEMENT

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