Analysis of experimental data on the effect of fire source elevation on fire and smoke dynamics and the critical velocity in a tunnel with longitudinal ventilation

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Abstract

A 1/3 scaled tunnel model was built to explore the effect of fire source elevation on fire and smoke behavior, and especially the critical velocity, in a tunnel with longitudinal ventilation. An experimental campaign has been carried out with a series of tests in 9 configurations, varying the fire size, ventilation velocity and fire elevation. Results in terms of combustion rate, ceiling temperature and critical velocity are discussed. If the flame reaches the ceiling when the fire source is elevated, the fuel burning rate increases by 15% due to increased heat feedback created by the part of the flame below the ceiling. The location of the maximum ceiling temperature can move towards the downstream region in such conditions. A variable named as the height of the effective tunnel, H' , was proposed to substitute the tunnel height, H , in the Li et al. model [1] to consider the effect of fire elevation in predicting critical velocity. The accuracy was illustrated by means of the results of the present tests and those of other research studies. Based on a dimensional analysis, three conditions are identified on the basis of the ratio of the flame height to the height difference between fire surface and the tunnel ceiling, $\frac{L_{fl}}{H'}$. This allows to demonstrate the variation of the critical velocity with changing fire elevations. The accuracy was illustrated by means of the results of the present tests and those of other research studies. The increase of fire elevation leads to the increase of the dimensionless variables $Q^* \left(\frac{W}{H'}\right)^{-1/4}$, $\frac{L_{fl}}{H'}$ and V^* (although this remains sometimes unchanged), rather than only a rise or

29 diminution of critical velocity.

30 **Keywords:** Tunnel, Fire, Fire elevation, Critical velocity, Longitudinal ventilation

31 **Nomenclature**

32	A_f	the fuel surface area (m^2)
33	$A_{f,w}$	the weighed oil pan surface area (m^2)
34	b_{f0}	the radius of fire source (m)
35	c_p	heat capacity of air ($kJ/kg \cdot K$)
36	D	fire diameter (m)
37	g	gravity acceleration (m/s^2)
38	H	height of the tunnel (m)
39	H_f	the elevation of the fire source (m)
40	H_{fl}	the flame height (m)
41	H'	the height difference between fire surface and the ceiling (m)
42	H'_1	the height difference between original fire surface and ceiling (m)
43	H'_2	the height difference between raised-up fire surface and ceiling (m)
44	ΔH_f	the complete combustion heat of the fuel (kJ/g)
45	L	length (m)
46	L_{fl}	the flame length (m)
47	$\overline{\dot{m}_{a,f}''}$	the average mass loss rate per unit area of different velocities in a
48		certain test ($kg/(m^2 \cdot s)$)
49	$\dot{m}_f''$	the mass loss rate per unit area of the fuel ($kg/(m^2 \cdot s)$)
50	$\overline{\dot{m}_f''}$	the mean mass loss rate per unit area over each quasi-steady-state
51		period ($kg/(m^2 \cdot s)$)
52	$m_{f,t}$	the fuel mass at time t (kg)
53	$m_{f,t+\Delta t}$	the fuel mass at time $t + \Delta t$ (kg)
54	N	the number of measured points
55	n	the measurement times

56	P	the level of confidence
57	Q	heat release rate (HRR) (kW)
58	Q_c	convective heat release rate (kW)
59	Q^*	dimensionless heat release rate
60	T	temperature (K)
61	T_0	ambient temperature (K)
62	$\Delta T_{max,0.98\text{ m}}$	the maximum temperature rise for fire elevation of 0.98 m (K)
63	$\Delta T_{max,0.18\text{ m}}$	the maximum temperature rise for fire elevation of 0.18 m (K)
64	t	time (s)
65	Δt	the time interval over the quasi-steady-state period (s)
66	U_{A,v_i}	a type-A standard uncertainty of v_i (m/s)
67	U_{B,v_i}	a type-B standard uncertainty of v_i (m/s)
68	$U_{m_{f,t}}$	the uncertainty of $m_{f,t}$ (kg)
69	$U_{m_{f,t+\Delta t}}$	the uncertainty of $m_{f,t+\Delta t}$ (kg)
70	$U_{\overline{\dot{m}_f}}$	the uncertainty of $\overline{\dot{m}_f}$ (kg/(m ² · s))
71	U_Q	the uncertainty of Q (kW)
72	$U_{\Delta t}$	the uncertainty of Δt (s)
73	$U_{\bar{v}}$	the uncertainty of $\bar{v}$ (m/s)
74	U_{v_i}	the uncertainty of v_i (m/s)
75	$U_{v_{a,meas}}$	the uncertainty of $v_{a,meas}$ (m/s)
76	V	critical velocity (m/s)
77	V^*	dimensionless velocity
78	v	velocity (m/s)
79	$\bar{v}$	the mean velocity in the measuring plane (m/s)
80	$v_{a,meas}$	the average value of the measured velocity (m/s)
81	v_i	the velocity of the i -th measured point (m/s)
82	$v_{i,j}$	the j -th measured value of v_i (m/s)
83	v_{nom}	the nominal velocity (m/s)

84	W	width of the tunnel (m)
85	Greek symbols	
86	ρ_0	ambient density (kg/m^3)
87	χ	the combustion efficiency
88	θ	the angle between the center line of the flame and the ground ($^\circ$)

89 **1 Introduction**

90 Tunnels are products of modern society and play an important role in the
91 economic development. However, along with it is the increasing rate of fire risk,
92 especially with huge traffic loads. When the fire takes place in the tunnel, forced
93 ventilation facilities are one option to create safe areas without smoke inside the
94 tunnel. Longitudinal ventilation is adopted as a common method to control the smoke
95 flow and establish a safe evacuation environment for people upstream of the fire
96 source. It is necessary to study the fire and smoke behavior characteristics under
97 longitudinal ventilation and many research studies have been conducted [2-4], mainly
98 focusing on the combustion rate [5-7], ceiling temperature [8-10], critical velocity [1,
99 11-22]. The combustion rate of a fire directly represents the magnitude of the heat
100 release rate, showing the scale and severity of the fire. The ceiling temperature during
101 a fire also needs to be determined to provide proper fire protection for the tunnel
102 structure. The critical velocity is a key parameter of a longitudinal ventilation system,
103 as it refers to the condition for which there is no smoke back-layering. The topic of
104 critical velocity has attracted special attention due to its importance for safe
105 evacuation and effective fire fighting and rescue in tunnel fires. Hence, it is the main
106 subject of the present paper.

107 Many semi-empirical and theoretical models have been established to predict the
108 critical velocities and the research is still ongoing. Based on the critical Froude
109 number, i.e., the ratio between inertial force and buoyancy, Thomas and Heselden et
110 al. [12, 13, 23] and Danziger [24] separately proposed the critical Froude number
111 should approach 1.0 and 4.5 at the critical condition. Besides, the critical Richardson

number, i.e., the ratio between inertial and viscosity forces, was also applied to examine the critical velocity in tunnel fires [25]. Oka and Atkinson [18] first introduced dimensionless heat release rate (HRR) and dimensionless critical velocity to analyze the data of both full-scale and reduced-scale tunnel tests, similar to Bettis et al. [26]. A method for scaling was proposed. The results showed that the value of (dimensionless) critical velocity varies with the one-third power of (dimensionless) HRR and will become nearly constant when the HRR exceed a particular value. This correlation had been proved appropriate and reasonable in the majority of studies [1, 11, 14-17, 20-22, 27, 28], including theoretical, experimental and computational analysis.

However, the critical velocity is also affected by many other factors of tunnel and fire source properties, such as geometry, obstruction, slope and fire source position, etc. The influence of tunnel cross-section was discussed by Wu and Bakar [14], using a series of small-scale tunnels with the same height but different cross-sectional geometry. Experiments and simulation results demonstrated the significant influence of tunnel cross-section on the critical velocity, and the hydraulic diameter was used instead of tunnel height. Li et al. [1] conducted both model tests and simulations to study the influence of tunnel cross section. The test results in other studies [14, 18] were also compared. The critical velocity showed to decrease with increasing tunnel height for small fires, but to increase for large fires. And it also showed to decrease with increasing tunnel width for small fires, but to be independent of tunnel width for large fires. The small fires and large fires were defined in the paper [1]. Li et al. [11] carried out another series of tests in two small-scale models to investigate the impact of accident vehicle obstruction. The results showed a decrease of critical velocity when obstructions existed upstream, probably due to stronger heat convection and radiation through reduced air entrainment. In order to study the effect of tunnel slope, a series of FDS simulations in two tunnels with various slopes, from -3% to 3%, were performed by Weng et al. [16, 17]. Prediction formulas modified by the tunnel slope, based on Li et al. [11], were presented. Ghassem et al. [21] performed another series

of FDS simulations to detect the impact of two fire sources in both lateral and longitudinal directions. The results revealed that the smoke behavior of two fire sources, in both perpendicular directions, was directly influenced by the distance between them. Besides, Wang et al. [27] adopted Fluent to investigate the effect of various fire horizontal positions. For the arched shape of the tunnel cross-section, the critical velocity of the fire next to the wall was higher than that of the ones in the middle and on the lanes. The ratio was around 1.12 in their researches. Apart from the fire horizontal positions, the fire vertical position, i.e., the fire elevation, was referred to by Tang et al. [22]. A hydraulic tunnel height was used in the model to consider the impact of the fire elevation [22]. The accuracy of the correlation was also proven by a number of tests on different scales by other researchers [14, 16, 19, 29].

In addition, some works have been done to explore the effect of external factors, like the surrounding environment [15, 22], exhaust system [30, 31] and FFFS (Fixed Fire Fighting Systems) [22]. In Tang et al.'s [22] study, two series of tests were conducted in ambient temperatures of nearly 10°C and 30°C separately in a 1/14 small scaled tunnel. The results showed that a lower critical velocity was required for the higher ambient temperature, probably due to the weaker smoke buoyancy on the ceiling. The effect of the water spray was also studied in [22]. Zhang et al. [15] carried out a series of numerical simulations in FDS to study the influence of high altitudes, i.e., reduced ambient atmospheric pressures. As the lower pressure led to the higher ceiling smoke temperature near the fire source, the required ventilation increased to prevent the back-layering smoke. Tang et al. [30] added a new non-dimensional factor to predict the back-layering distance, considering the ceiling extraction at the upstream side of the fire source.

There are many research studies that have focused on the aspect of combustion rate and ceiling temperature in longitudinally ventilated tunnel, to discuss the influence of the tunnel cross-section [5, 6, 32], tunnel slope [33, 34], transverse fire locations [35], and FFFS [36, 37].

However, the fire elevation in the above studies was unchanged for a certain

tunnel model, either with the fire surface set on the ground level or at a certain height. However, the fire elevation is not always a constant in the real fire scene. Hence, the effect of different fire elevations on the variation of combustion rate, ceiling temperature and critical velocity, while relatively unexplored, is relevant. Therefore, in this paper, sets of tunnel fire experiments have been conducted to study the effect of fire elevation on fire and smoke behavior, and especially the critical velocity, in a reduced-scale longitudinally ventilated model tunnel. Another main aim of this paper is to give a detailed description of this reduced-scale model tunnel, including the experimental setup, instruments, uncertainties and test methods, as basis for future research in which the FFFS will be introduced.

2 Description of experiments

A series of tests with longitudinal ventilation have been carried out in a reduced-scale model tunnel (see Fig. 1) that was built based on the Froude similarity law [4].

The width, height and length of the model tunnel were 3 m, 2.2 m and 30 m respectively. The model tunnel was constructed on a reinforced concrete ground and the side walls were 0.23 m thick, made up of brick and concrete (density 1900 kg/m^3 , heat conductivity $1.10 \text{ W/(m} \cdot \text{K)}$, specific heat $1.05 \text{ kJ/(kg} \cdot \text{K)}$). For convenience of preparation and observation work before and during the experiments, two 8-mm-thick fire-resistance windows were set on one side, which measured 1.92 m (length) $\times$ 1.47 m (height) each (see Fig. 1 and Fig. 2).

Fig. 1. A photo of the 1:3 model scale tunnel with longitudinal ventilation system

The longitudinal ventilation air flow was produced by six axial fans, which were distributed evenly at the entrance of the tunnel. Each fan was equipped with a 0.37 kW motor yielding a maximum capacity of 9500 m³/h (at 1450 rpm). All six fans were controlled simultaneously by a frequency modulator, which could adjust the rotational speed of the fans and thereby the flow velocity. In order to obtain a uniform flow inside the tunnel, a 0.5 m long rectifier was mounted 2.5 m downstream of the fans (see Fig. 2). The rectifier consisted of two 0.3-mm-thick steel wire meshes, with bore diameter of 1 mm and porosity of 76.9%, i.e. the ratio of opening area to total area. It was fixed across the cross section of the tunnel on the holder, and the longitudinal distance between them was 0.5 m. It is noted that the jet fans in a real tunnel are typically positioned under the ceiling instead of over the entire cross-section. However, for the convenience of the research and in the light of future numerical simulations, the fans were distributed evenly in Fig. 2 to create a relatively uniform and stable flow around the fire source.

Fig. 2. A schematic drawing of the model tunnel

Besides, although not activated in the current set of experiments, the water mist system is also already installed in the tunnel for future work. Fig. 3 gives an overview of the instruments in the tunnel experiments, including the weighing platform, anemometers, thermocouples and smoke observation aids.

Fig. 3. The layout during the experiments and photos of the instruments

2.1 Fire load and HRR measurement

99% pure industrial methanol was adopted as fuel during the experiments. Two kinds of pans were used as containers, both made of 3-mm-thick cast iron and 120 mm in depth, but with different surface size: one was 500 mm×500 mm and the other was 590 mm×840 mm (A1). The pan was placed on a weighing platform, consisting of a scale and a fire-proof board on it. In order to protect the scale from heat damage, glass wool was also used between the board and pans (see Fig. 4). The bottom of the fuel was 0.18 m from the ground and the distance between the centerline of fire load and the entrance of the tunnel was 16.50 m. In order to protect the ceiling part near the flame, a layer of 60-mm-thick glass wool (density 24 kg/m³, heat conductivity 0.04 W/(m·K), specific heat 0.70 kJ/(kg·K)) was fixed beneath the ceiling wall over a region of 1.68 m(length)×1.77 m (width).

The real-time weight data of the scale was collected at a rate of 1 per second and the accuracy was ± 0.02 kg. Four types of fire load were achieved through different layouts of pans in Fig. 4. The same pans were used in II、III and IV, but the long side of the pan in III was set parallel to the longitudinal direction of tunnel, as

opposed to setup II.

Besides, in order to verify the influence of the elevation of fire source on the critical velocity, which was already discussed in earlier work as well [22], two steel supports were adopted to hold the pans up to an elevation of 0.98 m and 1.3 m, as shown in Fig. 5. For safety reasons during the tests, the weighing platform was not used at the elevation of 1.3 m.

2.2 Velocity measurement and control method

The velocity measuring plane was placed 12 m upstream of the fire source and 5 hot-film anemometers were used during the experiments, as shown in Fig. 3, with measurement range of 0~2 m/s and an accuracy of 0.05 m/s. The measuring velocity values could be achieved from a data logging and processing system which was connected to the anemometers via RS485 communications, at a rate of 1 per second. In addition, in order to alleviate the impact of the instability of fans themselves, and in order to obtain a relatively steady flow velocity with a certain frequency of the motors,

an in-house developed feedback control system was adopted (see Fig. 6). The control mechanism is based on the collected velocity data and the target velocity value as set by the user. For example, if the collected data was higher than the set value, the control system sends an instruction to the frequency modulator to reduce the rotational speed of the fans.

Fig. 6. A schematic diagram of velocity control system

Fig. 7. The distribution of 49 velocity measuring points in the cross section using Log--Tchebycheff method

According to the standards on how to achieve the profile of flow speed in rectangular ducts [38, 39], the Log-Tchebycheff method with 7×7 symmetrically distributed points in the cross section was adopted. Fig. 7 presents the measurement scheme in a plane and the average value of the 49 measured points is regarded as the mean velocity over the entire cross section.

Fig. 3 displays that the anemometers were mounted on three poles and the relative position of each probe to the measuring plane could be changed, by adjusting the height of anemometer and the location of pole. As only 5 anemometers were available at a time in the experiments, the location of the probes was changed from one position to another to cover all the points. The velocity of a certain point refers to the average value of 3 minutes measuring values (1 measurement per second).

In Table 1, results from 12 velocity measurement campaigns are presented to show the velocity field along the tunnel. All Log-Tchebycheff-method results were

obtained with the 7-by-7 grid. Fig. 8 gives the relative location of velocity measuring planes adopted in Table 1.

Table 1 Summary and results of velocity measurement tests

Test #	Fans frequency (Hz)	Location of cross section (m) ^a	Smoke extraction system	Rectifier	$\bar{v}$ (m/s)	$U_{\bar{v}}$ ($\times 10^{-3}$ m/s)	RSD ^b
1	25	-12	NO	YES	1.04	7.31	9.56%
2	25	-9	NO	YES	1.02	7.26	9.30%
3	25	-6	NO	YES	1.04	7.24	11.68%
4	25	-3	NO	YES	1.04	7.33	9.57%
5	25	0	NO	YES	1.00	7.26	11.97%
6	25	+3	NO	YES	1.00	7.24	10.79%
7	25	+6	NO	YES	0.99	7.26	10.30%
8	25	+9	NO	YES	1.01	7.32	8.85%
9	15	-12	NO	YES	0.62	7.38	12.97%
10	35	-12	NO	YES	1.39	7.17	10.69%
11	25	+9	YES	YES	1.01	7.33	7.85%
12	25	0	NO	NO	1.32	7.19	18.97%

^a 0 m was the centerline of fire source, '-' referred to the locations upstream the fire source, '+' referred to the locations downstream the fire source.

^b Relative Standard Deviation. According to IEST [40], if $RSD \leq 15\%$, the uniformity level can be accepted.

$$RSD = \frac{\sqrt{\frac{1}{N-1} \sum_{i=1}^N (v_i - \bar{v})^2}}{\bar{v}} \times 100\%$$

where v_i is the velocity of the i th measured point (m/s) ; $\bar{v}$ is the mean velocity of all the measured points (m/s); And N is the number of measured points.

Fig. 8. Velocity measuring planes adopted to test the velocity distribution among the tunnel. 0 m was the centerline of fire source; '-' referred to the locations upstream the fire source; '+' referred to the locations downstream the fire source.

Before discussing the measurements, it is worthwhile to discuss the flow field as generated by the fans in more detail.

In order to evaluate the uniformity level of the velocity distribution in Table 1, an indicator was adopted according to the guidelines of IEST [40], identified as Relative standard deviation (RSD).

Results of Test #1-8 in Table 1 all satisfy the requirements for RSD, indicating that

the flow field was relatively stable and uniform from 12 m upstream the fire to 9 m downstream the fire (see Fig. 8). Fig. 9 shows the velocity profiles obtained at locations -12 m, 0 m and +9 m (Test #1, #5 and #8). The average velocity values of these three planes are basically constant (1.03 m/s, 1.00 m/s and 1.01 m/s, respectively) in the condition of the same fan frequency and environment. The uniformity of the measuring plane +9 m is obviously better than the other two planes in Fig. 9 and the distribution results have the lowest RSD in Test #1-8 of Table 1. This can be explained from the fact that eddies in the turbulent air flow induced by the axial fans become smaller through the rectifier and then smoothen continuously along the uniform section ducts.

In order to obtain enough space to study the back-layering phenomenon and protect the anemometers from heat damage, the location of the cross-section to control the velocity during the combustion was placed 12 m upstream of the fire. The control mechanism and method will be illustrated later in detail.

Fig. 9. Velocity profile obtained at plane -12 m, 0 m and +9 m (Test #1, #5 and #8 in Table 1)

Tests #1, #9 and #10 confirm that the uniformity of velocity distribution in the cross section 12 m upstream the fire was obtained over the range of 0.62 - 1.39 m/s (15 – 35 Hz fan frequency).

As the smoke extraction system was open during the burning, the influence of smoke extraction system was studied in Test #11. Table 1 shows that the effect of the flow velocity generated by the exhaustor on the velocity control could be ignored. Table 1 also shows that the distribution results failed to reach the standard of RSD of 15% at the position of the fire source when the rectifier was not used in Test #12.

With respect to the control of the flow, ideally, the mean value of the overall

measured points should be compared to the target value to get the best results (see Fig. 6), but only 5 probes were available in the present experiments. Therefore, it became important to sort out the most suitable five points to minimize the error between the average value obtained from them and compared to the value obtained from the 49 points. The 14 points in rows A and B (see Fig. 7) were excluded because the thermal smoke produced by methanol might reach and damage the anemometers if they were placed there. The other 15 points near the side wall and the ground were also not taken into consideration because the effect of obstruction was strong here. With the help of computer programs, the 5 points with the minimum deviation were picked from the remaining 20 points, based on the results of Test #1, #9 and #10 (see Table 1). The deviation value was within 0.01 m/s. The exact location of the 5 points is shown in Fig. 3.

The longitudinal air flow could be adjusted, ranging from 0.5 m/s to 1.4 m/s, with incremental change of about 0.1 m/s. Because the control system required some time to respond, the frequency of fans might produce fluctuations during this period. It was found that the deviation between the measured velocity ($v_{a,meas}$) and the nominal one (v_{nom}) remained within about 0.03 m/s in the tests (see Table 3 and Table 4). The $v_{a,meas}$ values in Fig. 10 and Table 4 are the average value of the measured velocity over the quasi-steady-state period (which is defined below in section 3.1).

2.3 Temperature measurement

Temperatures were measured with both sheathed 3 mm type K thermocouples and regular 0.3 mm type K thermocouples. All the thermocouples were installed along the longitudinal centerline of tunnel ceiling, in order to detect the front of back-layering. As shown in Fig. 3, sheathed thermocouples with the estimated highest temperature of 700 °C were fixed near the fire source (see gray ones in Fig. 3), and 0.3 mm type K thermocouples with the estimated highest temperature of 250 °C were placed at a certain distance from the flame (see black ones in Fig. 3). The measurement uncertainties of these two kinds of thermocouples were both 0.4% × the measured

value in °C . This meant the measurement uncertainties of 0.3 mm type K thermocouples were smaller than the 3 mm ones, and it was the reason why they were adopted. All the temperature data were collected every 4 seconds. The interval between thermocouples T-2~T+2 (positions: see Table 2) was 0.56m and the vertical distance between the ceiling and thermocouple was 0.08m. The interval of T-15~T-2 and T+2~T+14 was 0.75 m and the vertical distance between the ceiling and probe was 0.02 m. The positions of the thermocouples along the longitudinal centerline of the model tunnel are given in Table 2. Position 0 m is on the vertical centerline of the fire source. The expression of the positions is composed of '+'/'-' and its distance from the centerline of the fire source. '+' means the upstream side while '-' refers to the downstream side.

Table 2 The positions of thermocouples

Thermocouple No.	Thermocouple position	Thermocouple No.	Thermocouple position
T-15	-10.9 m	T 0	0 m
T-14	-10.1 m	T+1	+0.6 m
T-13	-9.4 m	T+2	+1.1 m
T-12	-8.6 m	T+3	+1.9 m
T-11	-7.9 m	T+4	+2.6 m
T-10	-7.1 m	T+5	+3.4 m
T-9	-6.4 m	T+6	+4.1 m
T-8	-5.6 m	T+7	+4.9 m
T-7	-4.9 m	T+8	+5.6 m
T-6	-4.1 m	T+9	+6.4 m
T-5	-3.4 m	T+10	+7.1 m
T-4	-2.6 m	T+11	+7.9 m
T-3	-1.9 m	T+12	+8.6 m
T-2	-1.1 m	T+13	+9.4 m
T-1	-0.6 m	T+14	+10.1 m

* '0 m' means the thermocouple is on the vertical centerline of the fire source; '-0.6 m' means the thermocouple is on the 0.6 m downstream the fire source; '+0.6 m' means the thermocouple is on the 0.6 m upstream the fire source.

2.4 Smoke observation

As no smoke particles were produced during the combustion process of methanol, smoke tracers were used. For the consideration of operational safety, the smoke tracers were ignited before the ignition of the fuel in the experimental process. Based

on the analysis work of the fuel mass loss rate and temperature evaluations, as illustrated later, a quasi-steady-state period in the model tunnel could be achieved about 8 minutes after igniting the methanol.

It has been reported that the spread and shape of the thermal smoke flow along the ceiling could be observed visually by means of laser sheet [41, 42]. A laser sheet with output power of 3 W was used in the experiments, positioned 0.8 m downstream of the tunnel exit and 0.05 m offset from the vertical centerline of the cross section to avoid the visual blockage effect by thermocouple piles in the centerline (see Fig. 3). When varying the fire source elevation, the elevation of the laser sheet was adjusted accordingly to make the observation more effective. During the entire burning process, the transport process and state of the smoke presenting in the laser plane were recorded by HD cameras. Four cameras were mounted on the window side of the tunnel wall (see Fig. 3), at distances 4.75 m, 9.75 m, 21.75 m and 26.35 m from the entrance, respectively.

2.5 Summary of test settings

Table 3 Summary of the tests

Test No.	Fire type	A_f (m ²)	W_f (m)	H_f (m)	v_{nom} (m/s)	$T_{a,0}$ (°C) ^a
1	I	0.25	0.50	0.18	1.0/0.9/0.8	34.2
2a ^b	II	0.51	0.84	0.18	1.1/1.0/0.9	30.5
2b	II	0.51	0.84	0.18	1.1/1.0	31.2
2c	II	0.51	0.84	0.18	1.0/0.9	30.9
3	III	0.51	0.59	0.18	1.2/1.1/1.0/0.9	30.3
4	IV	1.01	0.84	0.18	1.3/1.2/1.1	31.2
5	I	0.25	0.50	0.98	1.1/1.0/0.9	32.7
6	II	0.51	0.84	0.98	1.2/1.1/1.0	30.1
7	III	0.51	0.59	0.98	1.3/1.2/1.1	30.3
8	IV	1.01	0.84	0.98	1.4/1.3/1.2	31.3
9	I	0.25	0.50	1.3	1.2/1.1/1.0	30.2

^a The mean temperature values of all the thermocouples before the fire tests were presented here.

^b Three repeated experiments were conducted for Test 2, labeled as 2a, 2b and 2c.

Based on the experimental apparatus and instruments introduced above, a set of experiments was carried out to investigate the change in fire behavior and critical velocities under different conditions, varying the fire size and the elevation of the fire

source. Table 3 summarizes information of the conducted tests. Test 2 was carried out three times to verify the repeatability of the experiments.

3 Measurements and their uncertainties

3.1 Heat Release Rate (HRR)

Fig. 10 shows the evolution of fuel mass loss rate per unit area, $\dot{m}_f''$, and temperature rise for upstream thermocouples, from ignition to the decay stage for Test 1 (500 mm×500 mm oil pan, elevation 0.18 m, see Table 3). The nominal velocity values of 1.0 m/s, 0.9 m/s and 0.8 m/s were imposed successively in a single test. It should be noted that the longitudinal velocity was varied from a higher value to a lower one to observe the development of the smoke back-layering. The curve of $\dot{m}_f''$ has been smoothened using the five-point numerical differentiation method, with time step of 8 s [43]. As shown, a quasi-steady-state period under the actual velocity of 1.00 m/s is achieved during the period 450 s to 600 s, for both $\dot{m}_f''$ and temperature rise. The temperatures measured with thermocouples T-15~T-8 (see Fig. 3 and Table 2) are not presented, as they remained basically unchanged during the entire test, similar to T-7. For the velocities of 0.91 m/s and 0.81 m/s, quasi-steady state is observed during periods 950 s - 1100 s and 1300 s - 1450 s, respectively. The period time length of 150 s was also adopted in the data processing work of the other tests in Table 3. All the analyses below are based on the quasi-steady results.

(a) Evolution in time of fuel mass loss rate per unit area, $\dot{m}_f''$, (the value of $\overline{\dot{m}_f''}$ in each quasi-steady period is also presented) and velocity

(b) Evolution in time of upstream temperature rise

Fig. 10. Evolution in time of fuel mass loss rate per unit area, $\dot{m}_f''$, and upstream temperature rise in Test 1, with the nominal velocity of 1.0 m/s, 0.9 m/s and 0.8 m/s. (at the time of 0 s, the methanol was ignited)

The mean mass loss rate per unit area over each quasi-steady-state period, identified as $\overline{\dot{m}_f''}$, was calculated as follows:

$$\overline{\dot{m}_f''} = \frac{m_{f,t} - m_{f,t+\Delta t}}{A_{f,w} \cdot \Delta t} \quad (1)$$

In Eq. (1), $m_{f,t}$ and $m_{f,t+\Delta t}$ are the fuel mass at time of t and $t + \Delta t$; $A_{f,w}$ is the area of the weighed oil pan surface; and Δt is the time interval over the quasi-steady-state period, which is taken as 150 s for each condition. The uncertainty of $\overline{\dot{m}_f''}$, owing to the instrumental measurement [44], could be deduced from the following equation ($A_{f,w}$ was considered as a constant here):

$$U_{\overline{\dot{m}_f''}} = \sqrt{\left(\frac{\partial \overline{\dot{m}_f''}}{\partial m_{f,t}} U_{m_{f,t}}\right)^2 + \left(\frac{\partial \overline{\dot{m}_f''}}{\partial m_{f,t+\Delta t}} U_{m_{f,t+\Delta t}}\right)^2 + \left(\frac{\partial \overline{\dot{m}_f''}}{\partial \Delta t} U_{\Delta t}\right)^2} \quad (2)$$

where $U_{m_{f,t}}$, $U_{m_{f,t+\Delta t}}$ and $U_{\Delta t}$ are the uncertainties of $m_{f,t}$, $m_{f,t+\Delta t}$ and Δt separately. $U_{m_{f,t}}$ and $U_{m_{f,t+\Delta t}}$ are related to the accuracy of weighting scale, which is 0.02 kg; and $U_{\Delta t}$ is determined by the accuracy of weight recording system, which is the time interval of 1 s.

The value of $\overline{\dot{m}_f''}$ might be influenced by the ventilation conditions. Fig. 11 illustrates the variation of $\overline{\dot{m}_f''}$ with different levels of imposed longitudinal flow. The measurement uncertainties of $\overline{\dot{m}_f''}$ over each quasi-steady period, according to Eq.

(2), are also presented, ranging from 4.0×10^{-4} to 7.7×10^{-4} kg/(m² · s) (P=95%) for all the tests.

It is seen that for a certain fire type, when a longitudinal flow of 0.8 ~ 1.3 m/s is induced by the axial fans, the burning rates decrease, compared to the corresponding natural ventilation conditions, and the reduction is stronger for higher velocity. E.g., for tests of type II, under the nominal velocity of 1.1 m/s, the value of $\overline{m_f''}$ reduces by nearly 18% (from 0.0238 to 0.0196 kg/(m² · s)), while for 1.0 m/s and 0.9 m/s, it is 14% (to 0.0205 kg/(m² · s)) and 12% (to 0.0210 kg/(m² · s)), respectively. This is in accordance with the results of Saito et al [45-48] and Yao et al [49]: the burning rate of the methanol decreases with the increase of the longitudinal wind speed. However, this phenomenon only applies to relatively low air flow speeds, as demonstrated by Hu et al [50]: various sizes of methanol pool fires (square pans with length of 15, 20, 25 and 30 cm) were burned in a small-scaled wind tunnel (1.8 m wide, 1.8 m height and 6 m long), and the results indicated that with the increase of the longitudinal air flow, the burning rate of the methanol displayed first a decrease, and then an increase from 0 m/s to 3 m/s, with the turning point at about 1.5 m/s. This was explained by a change in the dominant mechanism of heat transfer to the fuel surface under different velocities. The reader is referred to [50-53] for more details for in-depth understanding the pool fire under wind conditions, but this aspect is not essential for the remainder of the present study. It suffices to state that the longitudinal velocities and corresponding burning rates are in accordance with the results of Hu et al [50] after numerical conversion by the Froude scale law, in the range of low wind speeds.

The behavior of burning rates depends on the orientation and pool size for identical ventilation conditions. For fires II and III, with the same pool size but different orientations, the burning rate of fire III is about 10% higher than fire II, for identical ventilation of 0.9 m/s, 1.0 m/s and 1.1 m/s. This phenomenon might be explained that the flames are blown backward more effectively for fire II, thereby reducing the heat feedback from the flames to the surface (see Fig. 12). The flame height and the deflection angle, θ , are nearly the same for fires II and III, see section 5.1. The similar

phenomenon was also observed in the study of Tang et al [53]: the burning rates with the shorter side facing the cross air flow showed faster than that with longer side for identical ventilation velocities. They also found that the flame with shorter side perpendicular to the air flow tended to be more turbulent with larger eddies above the fuel surface. For the tests of fire type □ and □, in Fig. 11 an increase of 1.1 m/s in the flow velocity causes the $\overline{m_f}$ values to drop by nearly 18% (from 0.0238 to 0.0196 kg/(m²·s)) and 11% (from 0.0280 to 0.0248 kg/(m²·s)), respectively. As shown in Fig. 4, the width of fire □ and □, i.e., the side perpendicular to the longitudinal air flow direction, is the same, while the length of fire □ is two times that of fire □. The reason for the higher burning rate of fire □ is again the stronger convective heat feedback from the flame to the fuel surface. This is confirmed, comparing the results of fire □ and □ (the width of them is almost the same, with 0.5 m and 0.59 m). Comparing fires □ and □ reveals a lower burning rate for fire □: the larger width leads to more heat loss by the wind flow.

Fig. 11. Mean mass loss rate per unit area over each quasi-steady-state period, $\overline{m_f}$, of different fire types in varied ventilation conditions, including the natural ventilation ones ($v_{nom}=0$ m/s). The elevation of the fire source is 0.18 m in all the conditions here.

Fig. 12. A schematic diagram for the flame appearance of fire II and fire III under the same ventilation conditions.

For the convenience of analysis and comparison work, the average mass loss rate per unit area for different velocities in a certain test, identified as $\overline{m_{a,f}''}$, is reported in Table 4. The uncertainty values are also listed, in the range of 4.0×10^{-4} to $7.7 \times 10^{-4} \text{ kg}/(\text{m}^2 \cdot \text{s})$ (P=95%).

From these values, the heat release rate (HRR) can be estimated:

$$Q = \overline{m_{a,f}''} \cdot A_f \cdot \chi \cdot \Delta H_f \quad (3)$$

where A_f is the fuel surface area, χ is the combustion efficiency and the ΔH_f is the complete combustion heat of the fuel. To calculate the HRR of methanol from Eq. (3), $\chi = 0.99$ and $\Delta H_f = 20 \text{ kJ/g}$ were adopted in this paper [3].

The HRR ranges from 109.2 kW to 571.2 kW in the model tunnel. If converted to the full scale according to the Froude scaling law, this corresponds to fires of 1.7 MW to 8.9 MW if a scale 1:3 is assumed. So the tests intended to model cars fire [4] in an urban tunnel, as most of long urban tunnels in China only allowed cars passed through. Meanwhile, for safety consideration of the tunnel model, fires with larger sizes were not adopted.

3.2 The ventilation system

As mentioned, the arithmetic mean value of the 49 measured points (v_i) based on the Log-Tchebycheff method was regarded as the average velocity ($\bar{v}$) over the measuring plane:

$$\bar{v} = \frac{1}{N} \sum_{i=1}^N v_i \quad (4)$$

where $N=49$ represents the number of measuring points.

According to JCGM [44], the uncertainty of $\bar{v}$ is given by

$$U_{\bar{v}} = \sqrt{\sum_{i=1}^N \left(\frac{\partial \bar{v}}{\partial v_i} U_{v_i} \right)^2} \quad (5)$$

where v_i can be obtained by

$$v_i = \frac{1}{n} \sum_{j=1}^n v_{i,j} \quad (6)$$

where $v_{i,j}$ refers to the j th measured value of v_i ; n refers to the number of measurements of the i -th measuring point. As the velocity of a certain point was measured during 3 minutes with a 1 s interval, $n=180$ was adopted here.

The standard uncertainty of v_i , U_{v_i} , can be calculated by [44, 54]

$$U_{v_i} = \sqrt{(t_p \cdot U_{A,v_i})^2 + U_{B,v_i}^2}$$

$$U_{A,v_i} = \sqrt{\frac{\sum_{j=1}^n (v_{i,j} - v_i)^2}{n \times (n-1)}} \quad (7)$$

where $t_p = 2$ is a factor corresponding to the confidence level of 95%; U_{A,v_i} is a type-A standard uncertainty, which is related to the fluctuations in the velocity (due to fluctuations in the ventilation system, as well as turbulent fluctuations); U_{B,v_i} is a type-B standard uncertainty and is related to the instrumental accuracy of the experimental hot-film anemometer, which is 0.05 m/s.

Table 4 Measurements results and uncertainties of each test in Table 3

Test No.	$\bar{m}_{a,f}^{\pi}$ (kg/(m ² · s))	$U_{\bar{m}_{a,f}^{\pi}}^c$ (kg/(m ² · s))	Q (kW)	U_Q (kW)	$v_{a,meas}$ (m/s)	$U_{v_{a,meas}}$ (× 10 ⁻² m/s)
1	0.0228	7.7×10 ⁻⁴	113.0	3.8	1.00/0.91/0.81	2.23/2.22/2.22
2a	0.0204	4.0×10 ⁻⁴	204.8	3.9	1.09/1.00/0.89	2.22/2.22/2.22
2b	0.0211	4.0×10 ⁻⁴	212.0	3.9	1.10/0.98	2.22/2.22/2.23
2c	0.0214	4.0×10 ⁻⁴	215.0	3.9	0.98/0.87	2.22/2.22/2.22
3	0.0217	4.0×10 ⁻⁴	218.2	3.9	1.18/1.08/0.99/0.89	2.22/2.23/2.23/2.22
4	0.0248 ^a	4.1×10 ⁻⁴	497.5	8.0	1.30/1.17/1.12	2.22/2.22/2.22
5	0.0221	7.7×10 ⁻⁴	109.2	3.8	1.14/1.02/0.92	2.23/2.22/2.23
6	0.0214	4.0×10 ⁻⁴	215.0	3.9	1.20/1.10/1.00	2.22/2.23/2.22
7	0.0220	4.0×10 ⁻⁴	221.1	3.9	1.28/1.21/1.12	2.22/2.22/2.22
8	0.0284 ^a	4.2×10 ⁻⁴	571.2	8.2	1.37/1.31/1.20	2.23/2.22/2.22
9	NA ^b	NA	111.1 ^d	NA	1.19/1.12/1.00	2.22/2.22/2.22

^a Two pans were used here and the values of the mass loss rate per area was the measured results of one pan.

^b Not available.

^c The average mass loss rate per unit area of different velocities in a certain test (P=95%).

^d Adopted as the average HRR value of Test 1 and 5.

According to Eqs. (6) and (7), U_{A,v_i} ranged from 5.05×10^{-4} to 6.84×10^{-3} m/s, U_{v_i} ranged from 5.0×10^{-2} to 5.2×10^{-2} m/s, and $U_{\bar{v}}$ ranged from 7.17×10^{-3} to 7.38×10^{-3} m/s. The values of $U_{\bar{v}}$ of each velocity measuring test in Table 1 are also presented.

The uncertainty value of $v_{a,meas}$, $U_{v_{a,meas}}$, can be calculated based on Eq. (4) ~ (7), among which $N=5$ and $n=150$. $U_{v_{a,meas}}$ ranged from 2.22×10^{-2} to 2.23×10^{-2} m/s, as shown in Table 4.

3.3 Repeatability

As mentioned, 3 repeat experiments were conducted for Test 2, labeled as 2a, 2b and 2c in the tables. Fig. 13 shows the ceiling temperature rise for the three sets of tests, illustrating that the temperature deviation was within 11.1% for identical ventilation velocity conditions. Also, the back-layering distance was measured to be identical (using the identification method as explained in section 4). Table 4 shows that the deviation in burning rate was less than 5.0%. All of this illustrates the good repeatability of the tests.

Fig. 13. Ceiling temperature rise for the same nominal velocities of 1.1 m/s, 1.0 m/s and 0.9 m/s for Test 2 in three different sets (2a: with the nominal velocities of 1.1 m/s, 1.0 m/s and 0.9 m/s successively; 2b: with the nominal velocities of 1.1 m/s and 1.0 m/s successively; 2c: with the nominal velocities of 1.0 m/s and 0.9 m/s successively)

4 Quantification of back-layering distance and critical velocity

4.1 *The identification of back-layering distance through temperature measurements and smoke observation*

The back-layering distance is defined as the longitudinal distance from the fire source to the front of the smoke layer at the upstream side. Both thermocouples and laser-assisted visualization have been used to determine this key parameter in the experiments.

The most direct observation is from the laser sheets visualization (Fig. 15). However, the presence of hot smoke has also been detected with thermocouples, by identifying temperature rise above ambient temperature. Comparing the temperature data to visual observations suggests that a temperature rise above 10 °C is characteristic for the presence of smoke (see below).

The back-layering distance cannot be determined at once, because it took about 10 minutes to obtain a stable temperature field after igniting the methanol with a certain ventilation velocity, as mentioned in section 3.1. Fig. 14 presents the stabilized temperature distribution under the ceiling for Test 1 with nominal velocities 1.0, 0.9 and 0.8 m/s. The temperature profiles refer to the average temperature rise over the stabilization period (of 150 s) at each thermocouple (see Fig. 10). Fig. 15 shows the smoke pictures at the upstream side, taken by camera 2, corresponding to the steady state in the nominal velocity of 1.0, 0.9 and 0.8 m/s, respectively. Good agreement between the two methods to identify the back-layering distance is found if the threshold temperature rise is set to 10 °C (marked spots in Fig. 14). Such good agreement has also been confirmed in the research of Kim and Han [42]. There are also small temperature increases at the thermocouples upstream of the marked spots in Fig. 14, especially in the conditions with relatively less back-layering. However, the video footage makes clear that the smoke did not arrive at these thermocouples. The measured temperature increase may be caused by thermal radiation from the flame. The furthest thermocouple positioned at the upstream side, with temperature rise

above 10 °C, is therefore taken to define the smoke back-layering distance in the experiments.

Fig. 14. Temperature distribution under the ceiling with ventilation velocity of 1.0, 0.9 and 0.8 m/s (Test 1)

Fig. 15. Smoke pictures with laser sheet in the nominal velocity of 1.0, 0.9 and 0.8 m/s (Test 1)

4.2 Critical ventilation velocity

The critical ventilation velocity is the minimum velocity to prevent the back-layering phenomenon in tunnel fires. Theoretically, this value can be calculated by plotting the longitudinal velocity vs. the corresponding back-layering distance data and then extrapolate the results to zero back-layering distance [14]. A sufficient number of data are needed to achieve a credible relatively linear extrapolation in this method and the required workload becomes heavy. Wu and Bakar [14] proposed that the ventilation velocity is almost equal to the critical value when the back-layering distance is very short (2.25 times the tunnel height in their work). The comparison between these two

methods was illustrated in the earlier work [22], using 0.5 times the tunnel height, showing a maximum error of 5%.

Considering the limited space at the upstream side in the model tunnel and the cost during the tests, the second method, allowing a certain degree of back-layering flow was used to determine the critical velocity value. For each test in Table 3, several ventilation conditions were conducted to find the critical value. As the ventilation velocity was controlled with intervals of 0.1 m/s during the experimental procedure, the results available from the tests were limited. For example, the conditions of 1.1 m/s, 1.0 m/s and 0.9 m/s were carried out for Test 2, and the corresponding back-layering distance was 0.6 m (T-1), 2.6 m (T-4) and 9.4 m (T-13). The velocity which would generate the back-layering distance such as 4.1 m (T-6) or 6.4 m (T-9), could not be achieved directly from the experiments. T-1 was eliminated because it was very close to the flame and even within the scope of the fire source in Test 4 and 8. Therefore, after comprehensive consideration of all the results, the temperature rise of T-2, T-3 or T-4, corresponding to distances of 1.1 m, 1.9 m and 2.6 m (0.5 to 1.18 times the tunnel height) upstream from the centerline of the fire source, was chosen to identify the critical ventilation velocity condition.

When the certain value was found, two more ventilation conditions were imposed, respectively 0.1 m/s below and above the critical velocity, to confirm the results. For example, in Test 1, as shown in Fig. 14, 0.9 m/s was the critical velocity, because T-2 was the last spot with temperature rise above 10°C, while in the conditions of 0.8 m/s and 1.0 m/s, the back-layering distance was longer and shorter than in the critical situation, which verified the reliability of results.

5 Results and discussion

5.1 The effect of the fire elevation on the fuel mass loss rate

Fig. 16 shows the average mass loss rate per unit area of fire type I ~IV with elevations 0.18 m and 0.98 m, i.e., Test 1 ~ 8 in Table 3 and Table 4. The horizontal

axis represents the ratio of flame height H_{fl} to the distance from the fire surface to the tunnel ceiling $(H - H_f)$. The flame height H_{fl} has been calculated as in [8]:

$$H_{fl} = \sin\theta \cdot L_{fl}$$

$$\sin\theta = \begin{cases} 1, & V' \leq 0.19 \\ (5.26V')^{-1/2}, & V' > 0.19 \end{cases} \quad (8)$$

$$V' = \frac{v}{w^*}, \quad w^* = \left(\frac{Q_c g}{b_{f0} \rho_0 c_p T_0} \right)^{1/3}$$

where θ is the angle between the center line of the flame and the ground; b_{f0} is the radius of fire source; Q_c is the convective heat release rate and is set here to 75% of the total heat release rate [55]; L_{fl} represents the flame length from Heskestad's formula [56]:

$$L_{fl} = -1.02D + 0.235Q^{2/5} \quad (9)$$

where D is the fire diameter. It should be noted that Eq. (9) applies to axisymmetric flames in quiescent environment. However, Heskestad [56] also reported that the effect of the wind on the flame length was minor for flame deflection angles up to 60° (i.e. when $\theta \geq 30^\circ$). All flames in the present study are within this scope. For a certain fire type, the mass loss rate per unit area remains similar when the fire source is raised from 0.18 m to 0.98 m, except for fire source IV, where an increase of approximately 15% is observed. This can be related to the ratio of H_{fl} to $(H - H_f)$, as shown in Fig. 16. For fire source IV, when the fire elevation changes from 0.18 m to 0.98 m, the $H_{fl}/(H - H_f)$ ratio increases from 0.52 to 0.94 (with $L_{fl}/(H - H_f)$ rising from 0.83 to 1.50). This means that the fire flames impinge onto the tunnel ceiling with higher elevation. For fire sources I ~ III, the values of $H_{fl}/(H - H_f)$ remain below 0.61 (with $L_{fl}/(H - H_f) < 1$) for both elevations, meaning that the fire flames do not reach the tunnel ceiling. These findings have been confirmed by video footage. When the fire flame reaches the tunnel roof, part of the flame is below the ceiling, creating more radiation and convective heat feedback (because the heat cannot 'escape') to the fuel surface, and thus enhanced fuel mass

637 loss rate.

638
639 Fig. 16. The relationship between the ratio of H_{fi} to $(H - H_f)$ and fuel mass loss rate per unit
640 area

641 5.2 The effect of the fire elevation on the ceiling temperature

642 Fig. 17 shows the ceiling temperature distribution in the tunnel for fire type I in
643 Test 1, 5 and 9, varying the fire elevation. The induced flow velocity is 1.0 m/s for
644 these three conditions. When the fire is raised to higher elevation, the ceiling
645 temperatures increase, as expected. The maximum ceiling temperature rise values
646 for the fire surface elevation of 1.3 m and 0.98 m are 3.7 and 1.1 times higher than for
647 the 0.18 m condition, respectively. There is also more smoke back-layering to the
648 upstream side. This is discussed extensively in section 5.3.

649 Fig. 18 provides the ratio of maximum ceiling temperature rise between fire
650 elevation 0.98 m and 0.18 m for various velocities for the four fire types. It is
651 interesting that the ratio values vary around 2.2, with maximum 12.5% deviation.

Fig. 17. Ceiling temperature distribution with the same ventilation velocity of 1.0 m/s for fire type I with different fire elevations

Fig. 18. The ratio of maximum ceiling temperature rise between fire elevation 0.98 m and 0.18 m for various velocities and different fire source

From Fig. 17, it can be deduced that the location of the maximum ceiling temperature moves closer to the center of the fire source when the fire source is elevated more. The same phenomenon was observed for fire type II with velocities 1.1 m/s and 1.0 m/s, but the conditions for fire type IV with velocities 1.3 m/s and 1.2 m/s show the opposite (see Fig. 19). Considering the analysis of $H_{fl}/(H - H_f)$ in Fig. 16, the fire type II conditions correspond to situations where the flames for neither the 0.18 m nor the 0.98 m fire elevations impinge onto the tunnel ceiling, as sketched in Fig. 20 (a). As the fire source is elevated from $H_{f,1}$ to $H_{f,2}$ and because the

cross-section of the holder is relatively small (so that the flow disturbance caused by the holder can be neglected), the entire flame of $H_{f,1}$ is essentially shifted vertically to the $H_{f,2}$ location. Consequently, the position of the maximum ceiling temperature shifts closer towards the fire source. However, when fire type IV is raised from 0.18 m to 0.98 m, the position of the maximum ceiling temperature moves downstream (see Fig. 19). This is probably because $H_{f1}/(H - H_f)$ increases from 0.52 to 0.93 (Fig. 16). The flame impinges onto the tunnel ceiling for the elevation of 0.98 m and its shape changes, getting more attached to the ceiling. Fig. 20 (b) sketches a possibility of the position modification in this situation, explaining for the above phenomenon. More experiments and studies are needed to confirm the phenomenon.

Fig. 19. Smoke temperature distribution for fire type II and IV in the fire elevation of 0.18 m and 0.98 m under the same ventilation velocities

Fig. 20. A schematic diagram for the position modification of the maximum ceiling temperature in two conditions: (a) flames do not impinge onto the ceiling for both elevations; (b) flames with the higher elevation impinge onto the ceiling, but the one in the lower elevation does not.

5.3 The effect of the fire elevation on the critical velocity

Table 5 The results of back-layering distance and critical velocity of each test in Table 3

Test No.	Q (kW)	v_{nom} (m/s)	L (m)	V (m/s)
1	113.0	1.0/0.9/0.8	0/1.1/4.1	0.9
2a	204.8	1.1/1.0/0.9	0.6/2.6/9.4	1.0
2b	212.0	1.1/1.0	0.6/2.6	1.0
2c	215.0	1.0/0.9	2.6/9.4	1.0
3	218.2	1.2/1.1/1.0/0.9	0.6/1.9/2.6/(over 7.1)	1.05
4	497.5	1.3/1.2/1.1	0.6/1.9/4.9	1.2
5	109.2	1.1/1.0/0.9	0.6/1.1/3.4	1
6	215.0	1.2/1.1/1.0	0.6/1.9/7.1	1.1
7	221.1	1.3/1.2/1.1	0.6/1.9/4.1	1.2
8	571.2	1.4/1.3/1.2	0.6/3.4/7.1	1.35
9	111.1	1.2/1.1/1.0	0.6/1.9/2.6	1.05

* In Test 3, 8 and 9, two ventilation conditions in a test meet the critical velocity requirements mentioned in section 4.2, thus the mean value of the two velocities is accepted here.

Based on the experimental procedure and methods illustrated above, the back-laying distances and critical velocities were obtained for the tests in Table 3, as shown in Table 5.

There is an important phenomenon should be noted in Table 5: the results illustrate that a higher critical velocity is required with elevated fires. A similar observation was reported by Oka and Atkinson [18]. They supposed this was because the vertical distance over which the plume was deflected was reduced and the acceleration of the inflow caused by the fire was reduced. However, Tilley et al. [57] reported seemingly opposite results for car park fire simulations. Although their work did not focus on the tunnel fire, the CFD simulation results for the critical velocity, mainly studied near the fire source in a rectangular car park (which can be seen as a wide tunnel), are relevant. The car park height was varied from 1.2 m to 10 m and the required critical velocity increased with increasing height in the range of 1.2 m to 2.2 m and then remained nearly unchanged (simulations were performed until a height of 10 m). They explained that the part of the flame impinging on the ceiling failed to add upward momentum to the fire-induced flow. Thus when the car park height increased, the flame could contribute more to this momentum and cause a higher critical velocity. Therefore, in view of these seemingly different observations, there is a need to study

the influence of fire elevation on the critical velocity.

There have been many theoretical equations to predict the critical velocity in tunnel fires based on the dimensional analysis of the experimental data, as mentioned previously. The correlation proposed by Li et al. [11] is as follows:

$$\begin{aligned} V^* &= 0.43[0.15]^{-1/3}[Q^*]^{1/3} \quad \text{for } Q^* \leq 0.15 \\ V^* &= 0.43 \quad \text{for } Q^* \geq 0.15 \end{aligned} \quad (10)$$

where V^* and Q^* refer to the dimensionless critical velocity and dimensionless heat release rate:

$$\begin{aligned} Q^* &= \frac{Q}{\rho_0 C_p T_0 \sqrt{gH^5}} \\ V^* &= \frac{V}{\sqrt{gH}} \end{aligned} \quad (11)$$

where ρ_0 is the ambient air density, C_p is the specific heat capacity, T_0 is the ambient temperature, and H is the tunnel height.

As mentioned in earlier work [22], and the work of both Li et al. [1] and Tilley et al. [57], for an elevated fire source, the plume produced by the fire is above the surface of the fuel and thus an effective tunnel can be defined, as shown in Fig. 21. This relates to the theory of Thomas [12] for the critical velocity, where it was determined from the buoyancy force of fire plume and the inertial force of inflow air. Therefore, the height difference between fire surface and the tunnel ceiling, i.e. the height of the effective tunnel, H' , should be adopted instead of the original one, H . And a new dimensionless analysis of heat release rate and critical velocity is described in Eq.(12). It should be noted here that the holder to raise the fire surface is not regarded as an obstacle, i.e., the variation of longitudinal flow near the fire caused by the existence of holder can be neglected. It is noted that the use of the height difference is also in line with [57], where identical values for the critical ventilation velocity were found for elevated fires in the original car park on the one hand, and fires flush with the floor in a car park with equivalently reduced height (fig. 9 in [57]).

Fig. 21. The targeted tunnel in analyzing the conditions for elevated fire should be replaced from (a) to (b)

$$Q^* = \frac{Q}{\rho_0 C_P T_0 \sqrt{g H'^5}}$$

$$V^* = \frac{V}{\sqrt{g H'}} \quad (12)$$

When the fire source is raised up, the aspect ratio, i.e. the ratio of width and height, $\frac{W}{H'}$, of the effective tunnel will increase. For example, when the fire type I was elevated from the height of 0.18 m (Test 1) to 0.98 m (Test 5), the value of $\frac{W}{H'}$ increased from 1.48 to 2.46. Apart from the height of the effective tunnel, the aspect ratio also influences the critical velocity, which has been explored by Li et al. [1]. Therefore, the model in [1] is adopted in the present paper, in which the height of the effective tunnel, H' , was proposed to substitute the tunnel height, H :

$$V^* = 0.43[0.15]^{-1/3} \left[Q^* \left(\frac{W}{H'} \right)^{-1/4} \right]^{1/3} \quad \text{for } Q^* \left(\frac{W}{H'} \right)^{-1/4} \leq 0.15$$

$$V^* = 0.43 \quad \text{for } Q^* \left(\frac{W}{H'} \right)^{-1/4} > 0.15 \quad (13)$$

where the corresponding Q^* and V^* are based on Eq.(12). It should be noted that Eq. (13) would not be applicable when considering other factors which would affect the critical velocity, like tunnel slope or water suppression systems.

Fig. 22 provides the plot of V^* vs. $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ defined in Eq. (12) for the data from the present tests, previous tests (a 1/14 scaled model) [22], other research work [1, 14, 16, 19] and two full-scale experiments [58, 59]. V^* first increases with increasing $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ and then becomes independent of $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ when the value

752 of $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ reaches around 0.10~0.16.

753 Considering the spreading in experimental data, fitting curves within the fitting
754 range in Fig. 22 could be accepted, such as Eq. (13). According to Eqs. (9) and (12), it
755 can be deduced that the dimensionless fire length, defined as $\frac{L_{fl}}{H'}$, is proportional to
756 the 2/5 power of $Q^* \left(\frac{W}{H'} \right)^{-1/4}$, as shown in Fig. 23. When the value of $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ is in
757 the range 0.10~0.16, $\frac{L_{fl}}{H'}$ reaches up to around 1.17~1.50, which can be interpreted
758 as an indicator to represent that the fire has developed into a “large fire” and the value
759 of V^* reaches its peak from then on. Hence, it is deduced from the experimental data
760 analysis that when the “large fire” happens, the flame of the fire attaches to the tunnel
761 ceiling.

762 When the fire is elevated, the height difference between fire surface and the tunnel
763 ceiling, H' , (see Fig. 21) is reduced. According to Eq. (12) and Fig. 23, the values of
764 $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ and $\frac{L_{fl}}{H'}$ increase with smaller H' for a certain fire size. However, the
765 value of V^* may remain unchanged. Here, three regimes will be discussed. A first
766 condition is such that both the original effective tunnel height H'_1 and elevated
767 effective tunnel height H'_2 are in the regime $\frac{L_{fl}}{H'} < 1.17 \sim 1.50$, i.e., neither of the fires
768 are a “large fire”. The relationship of their V^* and real critical velocity V will be $V^*_1 <$
769 V^*_2 (from Fig. 22 and Fig. 23) and $V_1 < V_2$ (from Eq. (12) and (13)). A second regime
770 is such that both of H'_1 and H'_2 are in the condition $\frac{L_{fl}}{H'} > 1.17 \sim 1.50$, i.e., both fires
771 are a “large fire”. The relationship of their V^* and critical velocity V will be $V^*_1 = V^*_2$
772 (from Fig. 22 and Fig. 23) and $V_1 > V_2$ (from Eq. (12)). Finally, in the condition of
773 $\frac{L_{fl}}{H'_1} < 1.17 \sim 1.50$ and $\frac{L_{fl}}{H'_2} > 1.17 \sim 1.50$, it becomes more complex. The relationship of
774 their V^* will certainly be $V^*_1 < V^*_2$ (from Fig. 22 and Fig. 23), but the relationship of
775 their critical velocity V will be difficult to judge, with the possibilities of $V_1 < V_2$, $V_1 >$
776 V_2 and $V_1 = V_2$. The results of the present tests could be explained by the first
777 condition, as is shown in Fig. 22 and Fig. 23.

778 The results of Tilley et al. [57] are in the second regime, where the experimental

results showed that the critical velocity decreased from 1.63 m/s to 1.54 m/s gradually
 with the elevated fire source, i.e., with the value of H' reduced from 2.2 m to 1.2 m.
 The corresponding values of $\frac{L_{fl}}{H'}$ increased from 1.15 to 2.11 (in which $L_{fl}=2.53$ m)
 and could be classified into the second condition above approximately. In addition, the
 results of the present tests and Oka and Atkinson [18] are in the first regime, in which
 the critical velocities were observed to increase with the elevated fire source. When
 the fire elevation increases from 0.18 m to 1.30 m, the values of $\frac{L_{fl}}{H'}$ change from 0.48
 to 1.50 in the present tests. When the fire was elevated from the ground to 0.13 m
 height, the values of $\frac{L_{fl}}{H'}$ ranged from 0.55 to 1.20 in the tests of Oka and Atkinson
 [18]. The values of $\frac{L_{fl}}{H'}$ are thus within the range of $\frac{L_{fl}}{H'} < 1.17 \sim 1.50$ with varied fire
 elevations, which suits the first condition above. All the $\frac{L_{fl}}{H'}$ results are presented in
 Fig. 23.

Therefore, the rise-up of the fire source in a tunnel can lead to an increase in the
 dimensionless quantities, i.e., an increase of $Q^* \left(\frac{W}{H'}\right)^{-1/4}$, $\frac{L_{fl}}{H'}$ and V^* (sometimes
 unchanged). However, this does not necessarily imply a rise of critical velocity V : it
 can increase, remain constant or decrease in different conditions.

Fig. 22. The V^* vs. $Q^* \left(\frac{W}{H'} \right)^{-1/4}$ according to Eq. (12).

Fig. 23. The relationship between $\frac{L_{fl}}{H'}$ and $Q^* \left(\frac{W}{H'} \right)^{-1/4}$

6 Conclusion

Experiments have been conducted to study the influence of fire elevation on fire and smoke behavior in a longitudinally ventilated model tunnel, with special focus on the critical velocity under a set of conditions. The heat release rate was varied from

109.2 kW to 571.2 kW. If a scale 1:3 is assumed, this corresponds to 1.7 MW to 8.9 MW in full scale.

When the fire was elevated, the burning rate remained nearly unchanged as long as the values of $H_{fl}/(H - H_f)$ remained below 1 for both original and elevated conditions, i.e., the flame does not reach the ceiling in both conditions. However, if the fire flame reaches the tunnel roof with higher elevation, the fuel mass loss rate increases (by about 15% for fire source IV when it was raised from 0.18 m to 0.98 m). This phenomenon was due to more radiation and convective heat feedback from the flame to the fuel surface.

When the fire was elevated, the ceiling temperature increased and caused more smoke back-layering. In addition, the location of the ceiling maximum temperature shifted to the different directions for fire source I and IV. A possible explanation has been given in the paper, based on the changes of flame shape.

A variable named as the height of the effective tunnel, H' , was proposed to substitute the tunnel height, H , in the Li et al. model [1] to consider the effect of fire elevation in predicting critical velocity. The accuracy was illustrated by means of the results of the present tests and those of other research studies. The critical velocity was shown to increase with the elevated fire in the paper tests. With the aid of a dimensional analysis, it could be deduced that the increase of fire elevation causes the increase of the dimensionless variations, i.e., $Q^* \left(\frac{W}{H'}\right)^{-1/4}$, $\frac{L_{fl}}{H'}$ and V^* (sometimes unchanged). When the value of $\frac{L_{fl}}{H'}$ reaches about 1.17~1.50, a “large fire” exists and the value of V^* remains unchanged at its peak. Three regimes were classified to demonstrate the changes of critical velocity with different fire elevations, in which H'_1 was the original hydraulic tunnel height and H'_2 was the elevated hydraulic tunnel height: (1) if $\frac{L_{fl}}{H'_1} < \frac{L_{fl}}{H'_2} < 1.17 \sim 1.50$, then $V^*_1 < V^*_2$ and $V_1 < V_2$; (2) if $\frac{L_{fl}}{H'_2} > \frac{L_{fl}}{H'_1} > 1.17 \sim 1.50$, then $V^*_1 = V^*_2$ and $V_1 > V_2$; (3) if $\frac{L_{fl}}{H'_1} < 1.17 \sim 1.50$ and $\frac{L_{fl}}{H'_2} > 1.17 \sim 1.50$, then $V^*_1 < V^*_2$ but the relationship of their critical velocity V would

have the possibilities of $V_1 < V_2$, $V_1 > V_2$ and $V_1 = V_2$. Therefore, the change of critical velocity could not be determined as a simple increase or decrease with the elevation of the fire source.

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