The combined effect of a water mist system and longitudinal ventilation on the fire and smoke dynamics in a tunnel

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Abstract

The individual and combined effect of a water mist system (WMS) and longitudinal ventilation (LV) on the fire HRR, smoke temperature and back-layering (BL) degree were explored in a 3 m (width)×2.2 m(height) ×30 m (length) tunnel model. A series of 39 tests has been conducted in 6 configurations, varying the velocity, water volume flow rate and nozzles arrangement. When the WMS or LV is imposed individually, the reduction effect on the HRR gets stronger with larger water volume flow rates or higher velocities. Yet, under the combined effect, the effect of the LV velocity on the HRR is non-monotonic: the HRR first reduces more, and then rises again with higher LV velocities for given WMS settings. The reduction in temperature monotonically increases with higher LV velocities, in contrast to the HRR behavior. The above phenomenon is explained to be due to the relatively 'low' flame height in the present paper, as a consequence of which the interaction between the flame and the water droplets mainly occurs in the lower part of the tunnel, while the interaction between the hot smoke and the water droplets mainly happens in the upper part. The fire HRR behavior mainly relates to the interaction in the lower part, while the temperature depends on both regions. Besides, for a certain BL distance, the required ventilation velocities reduce by 13% to 55% with activated WMS, compared to the same conditions without WMS. The effect of covering the fire with a shield is also discussed. For relatively small velocities, the fire HRR, smoke temperature and BL distance are larger with the shield in place.

Keywords: Water mist system; longitudinal ventilation; HRR; the maximum

temperature rise; smoke back-layering; tunnel fire

1 Introduction

In order to increase safety and prevent catastrophic damage in tunnel fires, Fixed Fire Fighting Systems (FFFS), such as Water Mist Systems (WMS), are considered in most long urban tunnels in China as a means of fire control and suppression. FFFS is nevertheless not a traditional fire protection system for tunnels in most countries due to the lack of design guidelines. In WMS, about 90% the droplets have a diameter of less than 500 μm [1]. The current paper will focus on water droplets in this range.

Carvel and Ingason stated in [2] that the main function of the WMS in tunnel fires is 'protection', rather than 'suppression'. The latter is defined in terms of ability to 'arrest the rate of fire growth and significantly reduce the energy output of the fire shortly after operation', which requires a substantial amount of water and has yet to be studied in details. Fire suppression [3-6] is beyond the scope of the current paper.

The aim of the present paper is to understand the impact on the fire and smoke dynamics of the WMS and LV individually and combined. Limited previous studies have focused on this means of smoke control in tunnels. Mid-scale tests and CFD simulations were conducted by Blanchard et al. [7] to understand the interaction between water mist drops and fire smoke in a longitudinally ventilated tunnel. Four major mechanisms of fire heat loss were identified and each of them was quantified, showing that the cooling effect of water drops accounts for the largest share, approximately 43%. Sun et al. [8] and Li et al. [9] treated the WMS as a water curtain and explored its ability to prevent smoke and heat spread with a reduced-scale model tunnel. The ratio of the water mist momentum to the smoke momentum is calculated for both tests in [9], with the obviously higher values in [8] than [9], therefore different results in terms of blocking efficiency were obtained. Sun et al. [10] reproduced the experiments in [8] and visualized the entrainment mechanism of the smoke by the water mists with the aid of FDS. It could be observed that due to the spray-induced impinging jets onto the floor, there appeared a clear upward flow motion between the nozzles, acting as a 'barrier' to block the smoke spread. The water mist curtain was

also studied in [11-13], to explore its ability to stop smoke spread, improve visibility and attenuate thermal radiation. However, it is noted that the effect of LV were not discussed and the water mist failed to block the smoke flow in [11-13]. Tang et al. [14] built a 1/14 small-scale model and placed two mist nozzles upstream the fire source. The results showed that lower LV velocities would be required to control smoke if the water mist was imposed to the tunnel near the fire, especially with higher pressure or more nozzles. The cooling effect of the water drops, along with the increase in inertial force of the longitudinal airflow induced by the water mists were supposed as the two main mechanisms for the smoke temperature reduction.

There are also some studies based on the water spray systems with relatively larger droplets (larger than 500 μm), which could be referential. In order to improve the basic understanding of water spray in longitudinal tunnel flow, two series of well-defined small-scale tests were conducted by Ingason [15] and Li et al. [16], with water spray system and automatic sprinklers, respectively. Ingason [15] used two wood cribs to simulate the HGV fires and investigated the possible fire spread between them. Besides, the effect of the water spray on the smoke temperature near the ceiling was studied by Ko et al. [17] and Wang et al. [18], with a full-scale and small-scale model tunnel, respectively. The results of both studies showed that the temperature decay along the longitudinal direction would be more significant with larger water volume flow rate. A method to predict the maximum temperature and temperature distribution near the ceiling was proposed, considering the water flow density and the water volume flow rates, respectively. The critical velocity was also studied by Ko et al. [17] and Wang et al. [19], showing that for a certain fire size, the required critical velocity would decrease with a larger water flow density (or water volume flow rate).

Then let us look at the combined effect of WMS and LV on the fire control. It is worth noting that in most of the studies mentioned above on smoke control, be it experiments or CFD simulations, the fire HRRs (Heat Release Rates) are set to be unchanged after the activation of the WMS (or the water spray system). The propane

fire is adopted in some of the studies to achieve the constant HRR [14, 17, 18, 20], as the gas flow rate could be easily maintained during the tests. In other tests using pool fires (heptane or methanol) [8, 9, 11], the WMS (or the water spray system) is placed at a certain longitudinal distance from the fire source. Therefore, the effect of the water droplets on the HRR is ignored. However, the HRR is not often the same before and after the WMS activation in real tunnel fire incidents, as the direct interaction between the water droplets and fire flame is common if the WMS is used to control (or reduce) the fire size. Several studies considered this aspect. In the mid-scale tests of Blanchard et al. [7], the WMS is set above the fire source (heptane pool fire) and the HRR reduces after the WMS activation. However, only one specific set of conditions in terms of LV velocity and WMS settings is considered in this study. Ingason [15] mentioned how the HRR performs after the activation of the water spray system, placed above a wood crib fire source. The results show that a larger water volume flow rate and a lower LV velocity leads to lower HRR. It is noted that only two LV velocity values (0.62 m/s and 0.21 m/s) are adopted. It can be seen in general that there is still a strong need to investigate this aspect thoroughly.

Therefore, in this paper, a series of 39 fire tests are carefully designed in a mid-scale tunnel to study the impact on the fire and smoke dynamics under the combined effect of WMS and LV. The WMS is placed right above the fire source, varying the water volume flow rate and layout. More importantly, the LV velocity is varied in a relatively wide range to take a closer look at its effect on the WMS and the smoke. Finally, the behavior of a fire source shielded at its top will be discussed.

2 Description of experiments

2.1 Tunnel model and fire source

All the experiments were conducted in a 3 m (width)×2.2 m(height) ×30 m (length) model tunnel, as shown in Fig. 1 (a) and (b). The ground is made of reinforced concrete and the side walls are made of brick and concrete. 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) × 1.47 m (height) each.

Fig. 1. A schematic drawing of the model tunnel and some detailed experimental set-up

Industrial methanol (99% pure) was used as fuel and poured into a 590 mm × 840 mm container positioned at 0.18 m from the ground, see Fig. 1 (c). The depth of the container was 120 mm and for safety consideration, the quantity of the fuel each time was controlled around the half capacity of the container. The distance between the centerline of fire load and the entrance of the tunnel was 22.50 m. The real-time weight data of the scale was collected at rate of 1 per second and the accuracy was ±0.02 kg.

2.2 Ventilation and temperature measurement

In order to alleviate the impact of the instability of fans themselves and obtain a relatively steady flow velocity with a certain frequency of the motors, an in-house

developed feedback control system was adopted. It consists of six axial fans (evenly distributed at the tunnel entrance, each with a 0.37 kW motor yielding a maximum capacity of 9500 m³/h), a frequency modulator, a 0.5 m long rectifier (with bore diameter of 1 mm and porosity of 76.9%) and hot-film anemometers (with the range of 0~2 m/s and an accuracy of 0.05 m/s). With the aid of Log-Tchebycheff-method, the locations of the five anemometers were selected in the velocity measuring plane, see Fig. 2, which was 4.5 m from the tunnel entrance, to measure and control the longitudinal velocity inside the tunnel. The velocity value was achieved at a rate of 1 per second. The detailed description of the ventilation measurement and control method are found in [21].

Temperatures were measured with both sheathed 3 mm type K thermocouples (see gray ones in Fig. 2, with the highest temperature of 700 °C) and regular 0.3 mm type K thermocouples (see black ones in Fig. 2, with the highest temperature of 250 °C). The measurement uncertainties of these two kinds of thermocouples were both 0.4% × the measured value in °C. All the temperature data were collected every 4 seconds. The positions of the thermocouples along the longitudinal centerline of the model tunnel are given in Table 1. Position 0 m (T0) is on the vertical centerline of the fire source. The vertical distance between the ceiling and probe was 0.02 m.

Fig. 2. The layout during the experiments and photos of the instruments

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Table 1 The positions of thermocouples

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

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

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thermocouple is on the 0.6 m downstream the fire source; '+0.6 m' means the thermocouple is on the

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0.6 m upstream the fire source.

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2.3 Water mist system (WMS)

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As shown in Fig. 1, the WMS consisted of a tank (2.0 m³, see Fig. 1 (f)), a pump

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(with the rated flow and pressure of 2.5 m³/h and 1.2 MPa), hydraulic relief valves,

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connecting pipes and nozzles. As the valves were worn out easily after frequent

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adjustments, three multiple relief valves were used in the present work to obtain the

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water pressure of 1.0 MPa, 0.5 MPa and 0.3 MPa (see Fig. 1 (e)). The spray pipe

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system was composed of one main pipe, with an outer diameter of 50 mm, and 5×3

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branch pipes, with the outer diameter of 20 mm. All the pipes were made of

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galvanized steel and were placed horizontally above the tunnel ceiling (see Fig. 1 (d)).

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A water mist nozzle was positioned at nearly 0.06 m below the roof at the end of each

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branch pipe, which was mounted vertically through the ceiling. There were overall 5

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rows, with an interval of 1.5 m, and 3 nozzles in each row, with an interval of 0.75 m.

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Each nozzle was equipped with a respective valve to control its opening, providing

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flexibility in the WMS. In addition, in order to reduce the pressure inside the pipes and

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protect the reducing valves when turning off the pump, a discharge valve was

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mounted between the reducing valves and nozzles.

2.3.1 Nozzle properties

Fig. 3. Pictures of the nozzle and its emerged water mist

The water mist nozzle considered herein (see Fig. 3 (a)), with an orifice diameter of 1.8 mm, produces a solid cone of fine water droplets with a spray half-angle θ , as shown in Fig. 3 (b). The spray picture, as shown in Fig. 3 (c), was also taken by means of a laser sheet, which shows the overall shape of the spray from the nozzle to the ground. The picture was taken in the experimental tunnel. Due to the limited space inside the tunnel, the front view of the laser image is unavailable. However, it can still be clearly observed that the spray exhibits a conical shape up to a certain distance from the nozzle before the gravitational force takes over the initial momentum and the spray shape becomes close to cylindrical, which is similar to the observations in [22] for a full cone water mist spray using the High Speed Camera.

Table 2 presents the water volume flow rate, half spray angle (θ), spray area and drop size distribution (DSD) for the imposed pressure of 0.3 MPa, 0.5 MPa and 1.0 MPa respectively. DSD was measured by the laser particle size measuring instrument, for all the droplets in the horizontal plane through the spray, 1 m below the nozzle, as prescribed in NFPA 750 [23]. The droplet diameters of all these droplets at a time point would be collected, and then the DSD could be counted and analyzed. The DSD of the water mist is expressed in terms of Cumulative Volume Fraction (CVF). The CVF of the droplets often agrees well with the Rosin-Rammler-lognormal curve [24]:

$$F_{V,D_d}(D_d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^{D_d} \frac{1}{\sigma D'} \exp\left(-\frac{[\ln(D'/D_{V,0.50})]^2}{2\sigma^2}\right) dD' & (D_d \leq D_{V,0.50}) \\ 1 - \exp\left[-\ln(2)\left(\frac{D_d}{D_{V,0.50}}\right)^\gamma\right] & (D_d > D_{V,0.50}) \end{cases}$$

$$\sigma = \frac{2}{\sqrt{2\pi(\ln 2)^\gamma}} \quad (1)$$

where $F_{V,D_d}(D_d)$ is the volume fraction of water in droplets of diameter smaller than D_d , $D_{V,0.50}$ is the volume-median diameter and γ is the distribution width parameter. $D_{V,0.99}$ corresponds to the diameter when the measured cumulative volume fraction of the droplets is 99%. It can be seen in Table 2 that when higher water pressure is imposed to the nozzle, the water volume flow rate and spray angle would become larger, and the droplets diameters would become smaller.

Table 2 Nozzle characteristics under different water pressures both in the model tunnel

Water pressure (MPa)	Water volume flow rate (L/min)	θ ($^\circ$)	Spray area (m^2)	$D_{V,0.50}$ (μm)	γ	$D_{V,0.99}$ (μm)
0.3	0.50	32.5	1.54	103	6.6	146
0.5	0.69	38.5	1.54	95	6.6	130
1.0	1.00	42	1.77	90	6.4	125

2.3.2 Nozzles set-up

Considering the inevitable differences between nozzles, the water volume flow rate of each experimental nozzle was measured before the tests. The latter varied from 0.88 L/min to 1.08 L/min at 1.0 MPa. Therefore, the nozzle arrangement was designed to ensure that the combined flow rate of the 3 nozzles in each row was around 2.96 L/min and the total of the 5 nozzles in each column was around 4.93 L/min (see Table 3).

Table 3 The water volume flow rates of all the experimental nozzles in the pressure of 1.0 MPa

Row number	Water volume flow rate in the column (L/min)			Total water volume flow rate in the row (L/min)
	Left	Middle	Right	
1	0.96	0.99	1.01	2.96
2	1.06	1.02	0.88	2.96
3	0.93	0.97	1.07	2.97
4	1.08	0.97	0.91	2.96
5	0.90	1.00	1.06	2.96
Total water volume flow rate in the column (L/min)	4.93	4.95	4.93	14.80

2.4 Summary of test settings

Based on the experimental apparatus and instruments introduced above, a set of experiments, including overall 39 tests in 6 configurations were carried out to investigate the fire and smoke behavior under the combined effect of WMS and LV (see Table 4). In Configuration 0, only ventilation was imposed in the tunnel. In Configurations 1 ~ 3, the water pressure varied (1.0 MPa, 0.5 MPa and 0.3 MPa). In Configuration 4, only the 5 nozzles placed along the longitudinal centerline were activated. In Configuration 5, a 1.0 m×1.0 m shield was added 1.1 m above the fire source, as shown in Fig. 1 (g). The LV was not activated in Tests 9, 17, 24 and 29, while the WMS was not activated in Configuration 0.

Table 4 Summary of the tests

Configuration No.	Test No.	Water pressure (MPa)	Nozzle number	Water flux (L/min)	Shield	v_{nom} (m/s)	$T_{a,0}$ * (°C)
0	1	/	/	/	No	1.1	15.8
	2					1.0	15.8
	3					0.9	15.8
	4					0.8	16.0
	5					0.7	16.0
	6					0.6	16.0
	7					0.5	15.5
	8					0.4	15.5
	9					0	16.1
1	10	1.0	5×3	15.0	No	1.0	15.1
	11					0.9	15.1
	12					0.8	15.1
	13					0.7	14.5
	14					0.6	14.5
	15					0.5	16.4
	16					0.4	16.4
	17					0	16.4
2	18	0.5	5×3	10.4	No	1.0	13.2
	19					0.9	13.2
	20					0.8	13.2
	21					0.7	16.4
	22					0.6	16.4
	23					0.5	16.4
	24					0	15.3

Configuration No.	Test No.	Water pressure (MPa)	Nozzle number	Water flux (L/min)	Shield	v_{nom} (m/s)	$T_{a,0}$ * (°C)
3	25	0.3	5×3	7.5	No	1.0	14.0
	26					0.9	14.0
	27					0.8	14.0
	28					0.7	14.2
	29					0	15.8
4	30	1.0	5×1	5.0	No	1.0	13.7
	31					0.9	13.7
	32					0.8	14.8
	33					0.7	14.8
5	34	1.0	5×3	15.0	Yes	1.0	12.1
	35					0.9	12.1
	36					0.8	12.1
	37					0.7	14.7
	38					0.6	14.7
	39					0.5	14.7

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

3 Measurement results and uncertainties

3.1 The identification of the quasi-steady state

The pool fire was not extinguished by the WMS in any of the tests. After activating the WMS, quasi-steady state conditions pertain, until the fuel is burnt out. Let us consider Configuration 1 as an example to introduce the quasi-steady state. Fig. 4 gives the evolution of the fuel mass loss rate, $\dot{m}_f$, and temperature rise for upstream thermocouples, starting from ignition, up to activation of nozzles. The nominal LV velocity values of 0.6 m/s, 0.5 m/s and 0.4 m/s (Tests 14, 15 and 16) were set successively in a single test to observe how the temperatures change with the ventilation conditions. As shown in Fig. 4, the WMS was activated 100 s after the fuel ignition, and after a while the temperature decreases due to the cooling effect of water mist. A quasi-steady-state period for the actual velocity of 0.60 m/s is achieved during 550 s to 700 s for both $\dot{m}_f$ and the temperature rise near the ceiling. For the velocities of 0.50 m/s and 0.40 m/s, quasi-steady state is observed during the time periods of 980 s to 1130 s and 1350 s to 1500 s, respectively. The period duration of 150 s was also adopted in the data processing work of the other tests in Table 4.

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

(b) Evolution in time of upstream temperature rise

Fig. 4. Evolution in time of fuel mass loss rate, $\dot{m}_f$, and upstream temperature rise in Configuration 1, with the nominal velocity of 0.6 m/s, 0.5 m/s and 0.4 m/s (at the time of 0 s, the methanol was ignited)

3.2 Heat release rate (HRR) and LV velocity

The heat release rate (HRR) in each test is estimated based on the mean fuel mass loss rate over its quasi-steady-state period (see Fig. 4), $\overline{\dot{m}_f}$:

$$Q = \overline{\dot{m}_f} \cdot \chi \cdot \Delta H_f \quad (2)$$

where χ is the combustion efficiency and the ΔH_f is the maximum (theoretical) heat of combustion of the fuel. To calculate the HRR of methanol from Eq. (2), $\chi = 0.99$ and $\Delta H_f = 20 \text{ kJ/g}$ were adopted in this paper [2]. It is assumed here that, given their relatively small size, very few droplets would reach the pan and affect the fuel mass loss rate measurements. In all tests, the amount of water ‘remaining’ in the oil pan after the burning has been confirmed very limited indeed ($\leq 0.0314 \text{ kg}$, which means $0.209 \times 10^{-3} \text{ kg/s}$ on average, which is negligible compared to the fuel mass

loss rate). Therefore, the value of the measured mass loss rate in the oil pan is treated equal to the value of the fuel mass loss rate, $\dot{m}_f$. The calculation method of the uncertainty has been introduced in detail in previous work [21]. Table 5 gives the HRR results for Configuration 0 ~ 5 under different velocities of 0 ~ 1.1 m/s, ranging from 104.7 kW to 234.0 kW, with the measurement uncertainty ranging from 3.8 kW to 4.0 kW. It is noted that the water droplets can be expected to affect the completeness of combustion, but this effect could not be quantified. This is believed not to alter significantly the overall trends in the temporal HRR profiles under the effect of the WMS, with or without LV.

Fig. 4 (a) also shows the LV velocity fluctuations over the quasi-steady-state period in the Configuration 1 due to the uncertainty of the ventilation system. The deviation between the measured velocity ($v_{a,meas}$) and the nominal one (v_{nom}) can be controlled within about 0.03 m/s in the tests (see Table 5). The uncertainty value of $v_{a,meas}$, $U_{v_{a,meas}}$, ranges from 2.22×10^{-2} to 2.23×10^{-2} m/s. The calculation method can be found in [21].

Table 5 Measurements results and uncertainties of each test in Table 4

Configuration No.	Test No.	Q (kW)	U_Q (kW)	$v_{a,meas}$ (m/s)	$U_{v_{a,meas}}$ ($\times 10^{-2}$ m/s)	ΔT_{max} (°C)	Position of ΔT_{max}	BL distance (m)	Critical velocity (m/s)
0	1	192.8	3.9	1.10	2.22	96.5	+0.6 m	0.6	1.0
	2	200.9	3.9	0.98	2.22	115.3	+0.6 m	2.6	
	3	206.5	3.9	0.90	2.22	140.6	+0.6 m	9.4	
	4	216.0	4.0	0.78	2.23	148.2	+0.6 m	NA*	
	5	218.0	4.0	0.71	2.22	160.1	+0.6 m	NA	
	6	223.7	4.0	0.62	2.23	174	+0.6 m	NA	
	7	228.0	4.0	0.50	2.22	190	0 m	NA	
	8	230.9	4.0	0.42	2.22	211	0 m	NA	
	9	234.0	4.0	0	2.22	249.1	0 m	NA	
1	10	132.1	3.8	0.98	2.23	16.8	+1.1 m	0	0.5
	11	123.9	3.8	0.92	2.23	17.6	+1.1 m	0	
	12	121.0	3.8	0.82	2.22	20.9	+0.6 m	0	
	13	110.9	3.8	0.69	2.22	28.2	+0.6 m	0.6	
	14	107.9	3.8	0.60	2.22	39.9	+0.6 m	1.1	
	15	113.8	3.8	0.50	2.22	47.2	0 m	2.6	
	16	120.7	3.8	0.40	2.22	46.1	0 m	7.1	
	17	140.8	3.8	0	2.22	75.6	0 m	NA	

2	18	156.0	3.8	0.98	2.23	27.7	+1.1 m	0	0.7
	19	157.0	3.8	0.89	2.22	29.9	+1.1 m	0	
	20	148.3	3.8	0.81	2.22	38.1	+0.6 m	0.6	
	21	121.8	3.8	0.71	2.22	38.2	+0.6 m	1.1	
	22	121.8	3.8	0.60	2.22	57.8	+0.6 m	4.9	
	23	126.7	3.8	0.49	2.23	58.5	+0.6 m	10.9	
	24	160.0	3.8	0	2.22	99.1	0 m	NA	
3	25	162.0	3.8	1.00	2.22	42.4	+1.1 m	0	0.9
	26	160.0	3.8	0.89	2.23	47.7	+1.1 m	1.1	
	27	156.0	3.8	0.81	2.22	67.2	+0.6 m	4.9	
	28	154.4	3.8	0.70	2.22	79	+0.6 m	NA	
	29	193.2	3.9	0	2.22	140.9	0 m	NA	
4	30	163.4	3.9	0.98	2.22	36.6	+1.1 m	0	0.9
	31	170.6	3.9	0.92	2.23	44.5	+1.1 m	0	
	32	151.5	3.8	0.77	2.23	61	+0.6 m	4.9	
	33	156.0	3.8	0.72	2.22	65.6	+0.6 m	10.1	
5	34	128.0	3.8	0.97	2.23	23.8	+2.6 m	0	0.6
	35	120.4	3.8	0.89	2.22	30.2	+2.6 m	0	
	36	113.0	3.8	0.81	2.22	32.2	+2.6 m	0	
	37	104.7	3.8	0.69	2.23	33	+2.6 m	0	
	38	126.1	3.8	0.60	2.22	48.4	+0.6 m	1.9	
	39	158.0	3.8	0.50	2.22	69.7	+0.6 m	7.1	

274 Not available.

275 4 Results and discussion

276 4.1 Effect of longitudinal ventilation (LV) only

277 The results of Configuration 0 (no WMS) are briefly discussed here, as they will
 278 serve as reference results to quantify the effect of the WMS.

279 4.1.1 Reduction in HRR

280 As shown in Fig. 5 (a), when the LV is imposed in the tunnel, the HRR decreases
 281 when compared to the natural ventilation condition (LV velocity = 0 m/s) and the
 282 reduction is stronger with higher velocities (up to around 17.6% for LV velocity of 1.1
 283 m/s). This is in line with the findings of Saito et al [25-28], Yao et al [29] and Hu et al [30]
 284 for methanol pool fires under wind conditions. It was explained in [30] that the pool rim
 285 and the fuel surface would be cooled convectively by the LV, leading to the HRR
 286 reduction. The detailed discussion has been presented in [21].

(a) The effect of LV velocity on the HRR and the ΔT_{max} (b) The dimensionless values of LV velocity, HRR and ΔT_{max}
 Fig. 5 The effect of the LV velocity on the HRR and the maximum temperature rise near the ceiling in the absence of the WMS (results of Configuration 0 are presented here)

4.1.2 Reduction in the maximum temperature rise

The measured maximum temperature rise near the ceiling, ΔT_{max} , a characteristic value for the smoke temperature, is shown in Fig. 5 (a) and Table 5. It decreases with higher LV velocities. Li et al. [31] proposed a correlation to predict the maximum temperature rise near the ceiling under the LV:

$$\Delta T_{max} = \begin{cases} \frac{Q}{vb_{f0}^{1/3} H_{ef}^{5/3}} & V' > 0.19 \\ 17.5 \frac{Q^{2/3}}{H_{ef}^{5/3}} & V' \leq 0.19 \end{cases} \quad (3)$$

$$V' = \frac{v}{w^*}, \quad w^* = \left(\frac{Q_c g}{b_{f0} \rho_0 c_p T_0} \right)^{1/3} \quad (4)$$

where b_{f0} is the radius of fire source; H_{ef} is the effective tunnel height (i.e., the vertical distance between the fire source and the tunnel ceiling); Q_c is the convective heat release rate and is set here to 75% of the total heat release rate [32]. The calculated results of the maximum temperature rise have also been shown in Fig. 5 (a). The deviations between the measurement and calculation results for the same LV velocities remain within 31%, which might be due to the different fuels used (methanol in the present paper versus propane in [31]).

For the ventilation conditions in the present paper, the value of V' is mostly above 0.19 (see Fig. 5 (b), the dimensionless values of HRR and the maximum temperature rise are also shown), which means that the maximum temperature rise depends not only on the fire HRR, but also on the LV velocity. On one hand, the reduction of the

maximum temperature rise is due to the fire HRR reduction with higher velocities, see Fig. 5 (a). On the other hand, when the imposed velocity increases, more cold air is mixed into the hot smoke, resulting in a further reduction of the smoke temperature rise.

4.1.3 Smoke back-layering (BL) distance and critical velocity

Fig. 6 presents the smoke temperature rise distribution near the ceiling. The temperature profiles refer to the average temperature rise over the stabilization period (of 150 s) at each thermocouple (see Fig. 4). It is clear that the smoke temperature spreads to both sides of the tunnel, exhibiting a symmetric distribution along the centerline of the fire source without LV imposed. Obvious temperature reductions appear along the tunnel when the longitudinal flow is imposed, especially at the upstream side and near the fire source. The higher the LV velocity, the more pronounced the temperature reduction. The position of the peak temperature rise is shifted backward as well (see Table 5).

Fig. 6 Temperature rise distribution near the ceiling under the velocities of 0 ~ 1.1 m/s in Configuration 0

The back-layering (BL) distance is defined as the longitudinal distance from the fire source to the front of the smoke layer at the upstream side. The furthest thermocouple with temperature rise of at least 10 °C is taken to define the smoke front position in the present tests, in agreement with earlier work [21]. Fig. 6 shows that the higher the LV velocity, the cooler the smoke upstream the fire source. For LV velocities above 0.9 m/s, the tunnel entrance becomes smoke-free. More specifically,

BL distances of 9.4 m, 2.6 m and 0.6 m are measured for LV velocities of 0.9 m/s, 1.0 m/s and 1.1 m/s, respectively (see Table 5). BL distances beyond 10.9 m cannot be measured, as this is outside the tunnel.

Normally, the critical velocity corresponds to the minimum required velocity when BL distance is 0 m. For convenience, the critical LV velocity is defined here as the velocity leading to BL distance of less than 2.6 m (the position of T-4) [21]. For Configuration 0, the value is 1.0 m/s (see Table 5).

4.2 Effect of water mist system (WMS) only

The results of Tests 17, 24 and 29 are discussed here, where only the WMS is imposed (Table 4 and Table 5).

4.2.1 Reduction in HRR

When the WMS is positioned above the fire source, the fire HRR is reduced from 234.0 kW (without the WMS in Test 9) to 140.8 kW, 160.0 kW and 193.2 kW under the water volume flow rate of 15.0 L/min, 10.4 L/min and 7.5 L/min, respectively, see Fig. 7 with the solid square dots. Generally speaking, there are four main mechanisms leading to the HRR reduction: gas phase cooling, oxygen displacement, fuel vapor dilution and fuel surface cooling [33]. However, fuel surface wetting is most likely limited in the scenarios of interest here, given the small size and the low momentum of the water droplets. It is noted that the evaporation of the water droplets plays an important role in the other three mechanisms, which explains why larger water volume flow rate (with smaller droplets and larger total droplet surface area) leading to the lower HRR.

4.2.2 Reduction in temperature rise

As shown in Table 5 and in Fig. 7 with the solid circle dots, there is a clear reduction in the maximum temperature rise, ΔT_{max} , by nearly 69.6%, 60.2% and 43.4% under the water volume flow rate of 15.0 L/min (Test 17), 10.4 L/min (Test 24) and 7.5 L/min (Test 29), respectively, when compared to the test without WMS (Test 9). In Eq.

(3) and (4) of Li et al. [31], the expected reduction of the maximum temperature is related to the reduction of the fire HRR only. The hollow circle dots in Fig. 7 refer to the calculated maximum temperature values based on $\Delta T_{max} = 17.5 \frac{Q^{2/3}}{H_{ef}^{5/3}}$ in Eq. (3), using the HRR estimated values in each condition. The under-estimation (by nearly 17.3%) for condition 9 (no WMS) is presumably due to the difference in fuels: propane in [31] versus methanol in the present study. Far more important is the observation that in the other three conditions, with the WMS activated, the values calculated from Eq. (3) are significantly higher than the measured temperatures, and the differences become larger with higher water fluxes. The sketch in Fig. 8 can help explain this phenomenon: due to the relatively 'low' flame height in the present study (lower than 1.1 m in the tests at hand), the interaction between the flame and the water droplets mainly happens below the mid-height of the tunnel. This directly reduces the fire HRR. Additionally, the interaction between the hot smoke and the water droplets mainly happens in the upper part, near the ceiling. This explains why the reduction in temperature is not only due to the reduction in HRR, but also due to the direct cooling of the smoke by the water droplets.

Fig. 7 The effect of the water volume flow rate on the HRR and the maximum temperature rise near the ceiling only with the WMS (using the results of Test 9, 17, 24 and 29)

Fig. 8. Sketch of the interaction between water droplets and flame in the lower part, and the interaction between water droplets and hot smoke in the upper part. The downward smoke displacement and the flame disturbance caused by the water droplets are not shown in this sketch

Fig. 9 shows the smoke temperature rise distribution near the ceiling in the above four tests. It is obvious that the hot smoke underneath the ceiling is cooled down effectively by the WMS in Tests 17, 24 and 29, compared to Test 9, especially with larger water volume flow rates (or higher water pressure). As there is no wind in the tunnel, symmetric temperature distributions along the centerline appear. In Test 9, the temperature rise peaks at the position above the centerline of the fire source and then decays along the tunnel away from the fire. Whereas in the other three tests with WMS, a 'dip' in the temperature is observed in the mist region near the fire source. This phenomenon is caused by water flux distributions determined by the nozzles' arrangements. For example, a relatively low temperature is observed at the location 0.6 m away from fire source, in between the two rows of nozzles near the fire source.

Fig. 9. Temperature rise distribution near the ceiling in Tests 9, 17, 24 and 29 (WMS only)

4.3 Combined effects of LV and WMS

After exploring the effect of LV and WMS individually, the combined effects are

discussed here.

4.3.1 Reduction in HRR

Fig. 10 (a) shows the HRR results for Configuration 0 ~ 4 under different velocities of 0 ~ 1.1 m/s, ranging from 107.9 kW to 234.0 kW, with the measurement uncertainty ranging from 3.8 kW to 4.0 kW (see Table 5). It is clear that when the water mist is imposed in Configurations 1 ~ 4, the HRR is reduced due to the cooling effect of the water droplets. The HRR reduction effect of the water suppression system is also observed by Blanchard et al. [7] and Ko et al [17] for heptane pool fires in a tunnel with longitudinal flows, but only one test was conducted in these studies.

(a) HRR values

(b) HRR reduction compared to Configuration 0 under the same velocities

Fig. 10. The HRRs and the reduction values under varied velocities

First let us look at Configurations 1 ~ 3, with 15 nozzles activated but various water volume flow rates. In line with section 4.2.1 (WMS only), the HRR reduction is more pronounced with larger water volume flow rates (Fig. 10 (a)). It is interesting to look at the effect of the LV velocity on the HRR. The HRR first decreases and then increases, with the turning point around 0.6 – 0.7 m/s (for Configurations 1 and 2), while with LV only (Configuration 0) the HRR decreases monotonically with velocity. In this respect it is important to note that the behavior of the water mist is influenced by the ventilation flow. Fig. 11 visualizes the water mist spray from the nozzle at hand (with water pressure 1.0 MPa) under various ventilation velocities with the aid of a laser sheet, along the centerline of the nozzle (see Fig. 2). When the LV is imposed, the water droplets gain longitudinal momentum from the imposed ventilation flow, deviating from their original track and flying towards the downstream side. The

deviation is more obvious for higher LV velocities (see Fig. 11 (a) and (b)). When the LV velocity exceeds a certain value, there is less water around the flame part to attenuate the fire (see sketch in Fig. 12). This leads to the assumption that the HRR is reduced by the LV and the WMS combined for velocities of 0 ~ 0.6 m/s, but when the velocity gets still higher, the decrease in heat transfer between the water and the flame leads to an increase in HRR. It should be noted that the maximum HRR variation in Configuration 1 (about 32.9 kW) exceeds the maximum experimental error bar (about 8.0 kW), but not by an order of magnitude. Therefore, there is a strong need for more experiments and studies to confirm the observed non-monotonic behavior.

Fig. 11 Water mist image of the experimental nozzle under different velocities with aid of laser sheet (1.0 MPa)

Fig. 12. Sketch of the interaction between water droplets, air flow and flame in the lower part, and the interaction between water droplets, air flow and hot smoke in the upper part.

Fig. 10 (b) presents the same information as percentages of HRR, using configuration 0 as reference under the same LV velocity conditions. These data thus present the reduction effect of the WMS on HRR in each test under various velocities.

It is interesting to note that Hu et al [30] conducted a series of experiments with different sizes of methanol pool fires under various ventilation velocities (without

WMS), and they observed that the HRR first exhibits a decrease and then an increase with higher velocities. This is similar to the HRR behaviors in Configurations 1~3 in the present study. They also found that the corresponding velocity values at the turning point would be larger with bigger fire sizes. As shown in Fig. 10, the HRR in Configuration 0 (without WMS) shows a decrease stage for all velocities of 0 ~ 1.1 m/s, which means that the velocity value at the turning point would be higher than 1.1 m/s. When the WMS is imposed (e.g., Configuration 1), the fire size is reduced due to the WMS and the turning point in Configuration 1 is around 0.6 m/s, lower than the turning point in Configuration 0, agreeing well with the results of Hu et al mentioned above.

Then let us examine Configuration 4, where only the 5 nozzles along the fire source centerline in the longitudinal direction were activated under the pressure of 1.0 MPa, with the total water volume flow rate of 5.0 L/min. As shown in Fig. 10 (b), the HRR reduction caused by the water mist in Configuration 4 and Configuration 1 is around 23.6% and 41.8% under the velocities of 0.7 ~ 1.0 m/s, which means the additional 10 nozzles near the tunnel wall in Configuration 1 contribute by only about 18.2% (=41.8%-23.6%) in reducing the HRR. In other words, the 5 nozzles along the fire source centerline play the dominant role among the total 15 nozzles in the fire control here. This is also confirmed when comparing Configuration 4 to Configuration 3. Although the total water volume flow rate of 5.0 L/min in Configuration 4 is less than that in Configuration 3 (7.5 L/min), the HRR reduction is similar under the velocities of 0.7 ~ 1.0 m/s in these two tests. The reason might be the higher water volume flow rate of the 5 nozzles along the fire source centerline in Configuration 4 (5.0 L/min) compared to in Configuration 3 (2.5 L/min).

4.3.2 Reduction in the maximum temperature rise

Fig. 13 gives the maximum temperature rise near the ceiling, ΔT_{max} , under various velocities and water fluxes, with the results of Configurations 0 ~ 3. It is obvious in the figure that whether the LV and WMS are used individually or together, ΔT_{max} decreases with higher ventilation velocities and larger water volume flow rates. The individual effect of LV and WMS has been introduced in section 4.1.2 and 4.2.2,

respectively. Under the combined effect of LV and WMS, e.g., with the highest velocity of 1.0 m/s and the largest water volume flow rate of 15 L/min (Test 10), the value of ΔT_{max} is reduced by up to 93.3% when compared to the test without LV and WMS (Test 9). As both the LV and WMS lead to the reduction in the maximum temperature, the effect of these two aspects will be discussed.

Fig. 13. The ΔT_{max} variations under various LV velocities and water volume flow rates

First let us consider the temperature reduction effect of the WMS. As shown in Fig. 14 (a), the maximum temperature rises near the ceiling in Configurations 1 ~ 5 are clearly lower than the ones in Configuration 0 under the same imposed velocities, which is partly due to the HRR reduction. As discussed in Fig. 10, for Configuration 1, the HRR first decreases and then increases when velocity increases from 0 m/s to 1.0 m/s, with the turning point around 0.6 m/s. However, the corresponding value of the maximum temperature changes differently in the range of 0.6 ~ 1.0 m/s: it keeps decreasing (or remains almost unchanged) with higher velocities.

(a) The maximum temperature rise near the ceiling in Configurations 0 ~ 4

(b) The reduction on the maximum temperature rise near the ceiling in Configurations 1 ~ 4 compared to Configuration 0

Fig. 14. The reduction effect of the WMS on the maximum temperature rise near the ceiling under various LV velocities

The different behavior of HRR and temperature when the velocity exceeds 0.6 m/s is linked to the relatively 'low' flame height in the present study (lower than 1.1 m in Configurations 1 ~ 4), see the sketch in Fig. 12. As introduced in section 4.2.2, the maximum temperature rise near the ceiling is not only related to the fire HRR, but also connected to the direct cooling effect of the local water droplets on the hot smoke. Fig. 15 presents the comparison of experimental data to values of the maximum temperature rise as calculated from Eqs. (3) and (4), using the HRR values as calculated from Eq. (2) with the measured fuel mass loss rates. In other words, these calculated values refer to the expected maximum temperature rise, resulting from the fire HRR (i.e., the region near the floor). Whereas it is not possible to quantify the expected reduction in completeness of combustion due to the water droplets (and hence the HRR to be used in expressions (3) and (4) is most likely lower than what was used here, keeping a combustion efficiency of 0.99), the results clearly suggest that the significantly lower experimental values (compared to the calculated values)

are due to direct cooling of the water on the smoke (in the region near the ceiling). For Configuration 0, with LV only and no WMS, the deviations between the calculation results and the experimental data for the same LV velocities remain within 31%, and the measured temperature rise is even higher than the calculated value for high enough LV velocity. As mentioned above, different fuels have been used (methanol in the present paper versus propane in [31]), which might explain differences observed. When the WMS is activated, the experimental values are always significantly below the calculated ones, with deviations up to 231% in Configuration 1 under LV velocity of 1.0 m/s. This suggests that the direct cooling effect of the water droplets on the hot smoke plays an important role in reducing the maximum temperature near the ceiling here. The results for Configurations 2 ~ 4 are qualitatively similar. It is noted that if the flame were high enough to impinge onto the ceiling, the water mist interaction is expected to affect the combustion efficiency even much stronger than in the present study and different changes in HRR and smoke temperature are expected. More experiments and studies are needed in the future to challenge this assumption.

Fig. 15. The comparison between the experimental results and the calculated results based on Eq. (3), in terms of the maximum temperature rise near the ceiling (using the results of Configurations 0 ~ 4)

In Fig. 14 (b), the reduction percentage of the maximum temperature rise in Configurations 1 ~ 4, compared to Configuration 0, is calculated presented

529 $\frac{\Delta T_{max,q=0} - \Delta T_{max}}{\Delta T_{max,q=0}}$. ΔT_{max} refers to the maximum temperature rise of the plotted condition.
530 $\Delta T_{max,q=0}$ refers to the maximum temperature rise of the condition without spray
531 system but with the same ventilation velocity as the plotted condition. It can be
532 observed that the cooling effect of the WMS is strengthened by the LV compared to
533 the natural ventilation. It tends to remain nearly unchanged when the velocity reaches
534 a certain value. For example, in Configuration 1, the reduction is about 70.0% under
535 the natural ventilation. It increases to 75.1% ~ 85.9% with velocities of 0.4 m/s ~ 0.8
536 m/s, and then remains almost constant with the velocities of 0.9 m/s and 1.0 m/s. This
537 phenomenon results from the combination of two mechanisms: on the one hand, as
538 discussed above, due to the existence of the LV, the reduction effect of the WMS on
539 the fire HRR first increases and then decreases with higher velocities (see Fig. 10 (b)).
540 On the other hand, the reduction effect of the WMS on the ceiling smoke could be
541 more significant under relatively high velocities.

542 Next, the temperature reduction effect of the LV is discussed. Fig. 16 (a) shows the
543 values of the maximum temperature rise near the ceiling for velocities of 0 m/s, 0.4 ~
544 1.0 m/s respectively, with the change of the water volume flow rate. The results of
545 Configurations 0 ~ 3 are used here. It is obvious that the maximum temperature rise is
546 lower with larger amount of water imposed, regardless of the velocity values. The
547 reduction percentage $\frac{\Delta T_{max,v=0} - \Delta T_{max}}{\Delta T_{max,v=0}}$ is reported in Fig. 16 (b). ΔT_{max} refers to the
548 maximum temperature rise of the plotted test. $\Delta T_{max,v=0}$ refers to the maximum
549 temperature rise of the test under natural ventilation but with the same water mist
550 setup as the plotted test. It can be observed that the existence of the water mist
551 enhances the cooling effect of the ventilation system, and the enhancement increases
552 with the higher water volume flow rates. This is because the air flow is cooled down in
553 the mist region, leading to a stronger temperature reduction effect to the ceiling smoke
554 (and the flame). There seems to be a linear relationship between the water volume
555 flow rate and the cooling effect of ventilation. However, more experiments and studies
556 are needed to confirm the rules.

(a) The maximum temperature rise near the ceiling under velocities of 0 ~ 1.0 m/s separately, with the change of water volume flow rate

(b) The reduction on the maximum temperature rise near the ceiling under velocities of 0.4 ~ 1.0 m/s compared to 0 m/s

Fig. 16. The reduction effect of the LV on the maximum temperature rise near the ceiling under various water volume flow rates

4.3.3 Reduction in smoke BL distance and critical velocity

Fig. 17 gives the temperature rise distributions near the ceiling in Configurations 0 ~ 4 under different water mist configurations but with the same ventilation conditions of 1.0 m/s, 0.9 m/s and 0.8 m/s. Obvious reductions in temperature rise appear along the tunnel in Configurations 1 ~ 4 compared to Configuration 0 under the same velocities, consistent with the reduction of the maximum temperature rise, as introduced in Fig. 14. It has been shown in Fig. 6 that in Configuration 0 (only with LV), the maximum temperature location would exhibit more obvious offset towards the downstream side with higher velocities. When the WMS is added in Configurations 1 ~ 4, see Fig. 17 and Fig. 18, the maximum temperature location is shifted in a similar manner under the same velocity conditions. Besides, as shown in Fig. 18, the location where a 'dip' appears between the nozzles in temperature distribution still appears when the LV is added, which was observed in Fig. 9 only with WMS, and it shifts from

the location around 0.6 m to 1.9 m away from fire source.

(a) 1.0 m/s

(b) 0.9 m/s

(c) 0.8 m/s

Fig. 17. Temperature rise distributions near the ceiling of Configurations 0 ~ 4 under the same velocity: (a) 1.0 m/s, (b) 0.9 m/s, (c) 0.8 m/s.

(a) Configuration 1 (1.0 MPa)

(b) Configuration 2 (0.5 MPa)

(c) Configuration 3 (0.3 MPa)

Fig. 18. Temperature rise distribution near the ceiling under different ventilation velocities in Configurations 1~3

As shown in Fig. 17, under the same imposed velocities, the tests with WMS have less BL than the ones without WMS. Fig. 19 (a) presents the smoke BL distances. The velocity conditions in which the BL distance exceeded 10.9 m are not shown, as this is outside the tunnel. For Configurations 1~3, the velocity value where the smoke BL

first appeared was 0.7 m/s, 0.8 m/s and 0.9 m/s, respectively, indicating that the smoke control effect is stronger with larger water volume flow rates with the same nozzles activated. The results in Configurations 3 and 4 are almost the same, which means the nozzle location matters for the smoke control.

Another interesting observation concerns the impact of the WMS as long as the BL distance is within the water mist region ($BL \leq 2.5$ m, see Fig. 1): the BL distance is much less sensitive to the LV velocity, compared to configuration 0 (no WMS), especially for Configurations 1, 2 and 5, which have higher water volume flow rates. This shows that the hot smoke inside the mist region is also cooled and blocked by the WMS, not only by the LV.

(a) BL distance in Configurations 0 ~ 5 (b) Velocity reduction rate in Configurations 1 ~ 5 compared to Configuration 0
 Fig. 19. Smoke BL distance and the velocity reduction rate in Configurations 1 ~ 5

In Fig. 19 (b), v_L represents the required LV velocity for a given BL length, L , in Configurations 1 ~ 5. v_{L0} represents the required LV velocity in the tests only with LV (i.e., Configuration 0) but with the same BL length, L . In order to study the effect of the WMS on the smoke BL distances more clearly, the velocity reduction rate, $\frac{v_{L0} - v_L}{v_{L0}}$, is reported. It is obvious that the required LV velocities with WMS are smaller than the ones without WMS for the same BL distance. This means that if the WMS is added in a tunnel, the ventilation equipment can consist of smaller fans. The reduction rate is shown to be in the range of 13.0% to 55.2% under various WMS arrangements in the present tests. The reduction rate for a certain WMS setup becomes nearly constant for larger BL distances. The reduction value depends on the water volume flow rate, nozzles arrangement and the presence or not of a shield (see next subsection). This

is an important finding for the design of combined LV and WMS. More research studies are needed to confirm and quantify this.

Finally, as the critical velocity corresponds to the velocity value when the BL distance is less than 2.6 m in the present study, the required critical velocity is reduced by 13% ~ 50% with the WMS setup in the present study.

4.3.4 *Effect of the shield over the fire source*

Under the same WMS setup as Configuration 1, Configuration 5 was constructed to explore the effect of a 1.0 m×1.0 m shield, placed 1.1 m above the fire source, see Fig. 1 (g). The shield is made up of several steel bars with a layer of 60-mm-thick glass wool lying on top. In order to prevent the water to soak the glass wool, a waterproof cloth covered its top surface. As shown in Fig. 20 (a), the HRR in Configuration 5 is significantly higher than in Configuration 1 for relatively low LV velocities (0.5 ~ 0.6 m/s), while the difference becomes small with higher LV velocities (0.7 ~ 1.0 m/s). This suggests that the thermal feedback to the fuel from the flames, blocked underneath the shield, is larger for these lower LV velocities, while the tilted flames for higher LV velocities are less affected by the presence of the shield. There could also be a different impact from the water droplets on the flames. This remains to be investigated. The values of the maximum temperature rise near the ceiling are also presented in Fig. 20 (a). These are always higher when the shield is in place, indicating a reduced cooling effect from the WMS. The dimensionless values of the LV velocity, HRR and the maximum temperature rise are also given in Fig. 20 (b).

Fig. 21, showing the evolution of the maximum temperature rise near the ceiling along the tunnel, provides more insight. For LV velocities of 0.8 m/s or higher, the profiles with shield are essentially shifted more downstream. The flames, tilted backward, are still somewhat blocked by the shield first and hence their tip is more downstream. For LV velocity 0.6 m/s, and even much more so for 0.5 m/s, the flame tilting is much less and, as mentioned, the HRR value is significantly higher with the shield in place. This leads to significantly higher temperatures upstream of the fire source for LV velocity 0.5 m/s, with significantly more BL than without the shield. This

is less pronounced, yet visible, for 0.6 m/s LV velocity. For these relatively lower LV velocities, the temperature profiles from the fire source onward and downstream are qualitatively similar (i.e., there is no downstream shift of the profiles). The LV velocity of 0.7 m/s denotes the demarcation between the two regimes for the study at hand. It is reminded that Table 5 summarizes quantitative results.

As closing note, it is mentioned that the fire condition in Configuration 5 could resemble a car fire, where the shield resembles the roof of the car. The results indicate that inclusion of a shield, to represent the roof of a car, seems interesting to obtain results, representative of reality.

(a) The values of LV velocity, HRR and ΔT_{max} (b) The dimensionless values of LV velocity, HRR and ΔT_{max}
 Fig. 20. The (dimensionless) values of HRR and the maximum temperature rise near the ceiling in Configurations 1 and 5

Fig. 21. Temperature rise distributions near the ceiling under the velocities of 1.0 ~ 0.5 m/s in Configurations 1 and 5

5 Conclusions

Experiments have been conducted to study the fire and smoke dynamics under the individual and combined effect of WMS and LV. The maximum HRR was around 234 kW and the fire flame height remained below 1.1 m (half the tunnel height), implying that only relatively small fires have been addressed in the present paper. The main conclusions are as follows:

(1) Due to the relatively low flame height, the interaction between the flame and the water droplets mainly occurs near the floor ('lower region' of the tunnel), regardless of whether or not LV was imposed. This led to a reduction in HRR. The interaction between the hot smoke and the water droplets mainly happens in the upper region. This led to smoke cooling. Both aspects (i.e., reduction in HRR and smoke cooling) have been shown to have a significant impact on the measured temperature rise near the ceiling.

(2) When only LV is imposed in the tunnel, the fire HRR decreased monotonically from 234 kW to 193 kW as the LV velocity increased from 0 m/s to 1.1 m/s. However, when the WMS is added, the HRR decreases (from 141 kW to 108 kW) as the LV velocity increased from 0 to 0.6 m/s, but then increased again (to 132 kW) for higher LV velocities (up to 1.0 m/s). This shows that when the LV velocity exceeds a certain value, there is less water in the flame region to attenuate the fire.

(3) In contrast to the non-monotonic behavior in fire HRR, the maximum temperature rise near the ceiling decreases monotonically with increased LV velocity, regardless of whether or not the WMS is activated. This allows to conclude that the direct cooling effect of the water droplets in the upper hot smoke plays an important role in the reduction of the maximum temperature rise.

(4) The reduction effect on the maximum temperature rise of the WMS and the LV has been quantified based on the values of $\frac{\Delta T_{max,q=0} - \Delta T_{max}}{\Delta T_{max,q=0}}$ and $\frac{\Delta T_{max,v=0} - \Delta T_{max}}{\Delta T_{max,v=0}}$, respectively. The reduction effect of a certain WMS first increases and then becomes constant with higher LV velocities, while the reduction effect of the LV is strengthened with higher water volume flow rates. This suggests mutual reinforcement on the

reduction of the maximum temperature rise near the ceiling.

(5) For a given BL distance, the required LV velocities with the WMS are reduced by around 13% to 55%, compared to the ones without the WMS in the present paper. This means that smaller fans could be adopted if the WMS is installed. Besides, it was shown that for a certain WMS setup, the velocity reduction rate, $\frac{v_{L0}-v_L}{v_{L0}}$, tends to be constant with various BL distances.

(6) The reduction effect of WMS on HRR, temperature and BL distance gets stronger with larger water volume flow rates for a given nozzle arrangement, as shown from Configurations 1 ~ 3. The results of Configuration 4 show the importance of the nozzle location for fire and smoke control. As the fire is placed along the longitudinal centerline of the tunnel, the nozzles along this line are more influential than the others.

(7) The presence of a shield (Configuration 5) is important. It leads to an increased HRR for low LV velocities (below 0.7 m/s in the present study). With low LV velocities (0.6 m/s or lower in the present study) it also leads to stronger back-layering. For higher LV velocities (beyond 0.7 m/s in the present study) the main effect of the shield is a downstream shift and increase of maximum temperatures near the ceiling, due to backward tilting of the flames (which are blocked by the shield).

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