Investigation on the characteristics of fire burning and smoke spreading in longitudinal-ventilated tunnels with blockages

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Abstract

The present study investigated the ventilation and blockage effect on fuel burning rate, the maximum temperature, critical velocity, and smoke back-layering length in longitudinally ventilated tunnels. Quantitative analysis was carried out by analyzing massive experimental measurements from the published literature. Three typical blockage modes were extracted to illustrate the blockage effect. Results indicated that fuel burning rate exhibited different responses towards the longitudinal ventilation, wherein burning rate of acetone, gasoline, ethanol, heptane, and wood crib increased when the wind velocity increased from 0.0 m/s to 3.0 m/s while burning rate of methanol pool fire firstly decreased and then increased. Prediction of the maximum temperature in tunnels without blockage by using previous correlations agreed well with the literature data. However, the maximum temperature was poorly estimated when the blockage effect was introduced. Modified correlations were thus established considering different blockage ratios. Meanwhile, empirical formulae to calculate the critical velocity and smoke-back-layering length in tunnels with and without blockages were also proposed, presenting good agreement with the measurements from previous literature.

Keywords**:** Blockage ratio; Heat release rate; Maximum temperature; Longitudinal ventilation; Smoke spread; Tunnel fire

Nomenclature

Nomenclature	
A	Area (m^2)
H	Height (m)
W	Width (m)
L	Length (m)
g	Gravity (m/s^2)
T	Temperature (°C)
$\dot{m}$	Burning rate (g/s)
Q	Heat release rate (kW)
V	Longitudinal ventilation velocity (m/s)
l^*	Dimensionless length
Q^*	Dimensionless heat release rate
V'	Character ventilation velocity
V^*	Dimensionless ventilation velocity
F_r	Froude number
ρ_a	Air density (kg/m^3)
Ri	Richardson number
V_c	Critical velocity (m/s)
$F_r{}'$	Modified Froude number
T_a	Ambient temperature (°C)
b_f	Diameter of fire source (m)
C_p	Specific heat of ambient air (kJ/kg·K)
$V_c{}^*$	Dimensionless critical velocity
Q_c	Convective heat release rate (kW)
ΔH_c	Specify heat of combustion (kJ/g)
V^*_{local}	Dimensionless local velocity
Subscript	
t	Tunnel
a	Ambient
b	Blockage
f	Full-scale
m	Reduced scale
ef	Effective
bf	Blockage-fire
sb	Smoke back-layering
max	Maximal value
$local$	Local value
Greek letters	
λ_s	Scaling ratio in Tables
χ	Combustion efficiency in Eq. (1)
θ	Flame deflected angle in Eq. (2)
γ	Coefficient in Eq. (4)
ε	Coefficient in Eq. (4)
φ	Blockage ratio in Eq. (6)

1. Introduction

Tunnel fires can result in huge property losses and casualties. There is a rich body of literature about tunnel fire dynamics and smoke control methods in the past few decades. Previous investigations covered a wide range of research topics, including but not limited to, the fuel burning rate (Roh et al., 2007; Hu et al., 2009; Shi et al., 2020), flame behavior (Sjöström et al., 2015; Tang et al., 2021), maximum temperature (Li et al., 2011; Fan et al., 2016; Yao et al., 2021), gas transportation (Zhang et al., 2012; Tang et al., 2014; Yu et al., 2020), and smoke control (Oka and Atkinson, 1995; Yu et al., 2018; Han et al., 2021b), etc. The relatively large number of theoretical and experimental investigations have built a solid theoretical foundation. However, new challenges continuously evolve due to the rapidly changing designs of modern tunnels.

In tunnels, longitudinal ventilation is prevalently utilized as an efficient and relatively low-cost smoke control strategy. The concept of longitudinal ventilation is to achieve a smoke-free region upstream of the fire for evacuation and to discharge the smoke flow through the downstream tunnel portal (Guo et al., 2012; Fan and Yang, 2017; Shi et al., 2021). Ventilation velocity to approach the zero smoke back-layering length is known as the critical velocity. Extensive research efforts were devoted to the critical state as well as the calculation of critical velocity. Oka and Atkinson (1995) were among the first few to investigate the effect of pool shape, fire size and fire location on the critical velocity by conducting fire tests in a model-scale tunnel. They proposed simplified formulas to estimate the critical velocity against either small or large fires. Through reduced-scale tests with three different fuels at various heat release rates, Roh et al. (2007) explored the ventilation effect on pool fire burning rate and discussed the relationship between the critical velocity and heat release rate. Weng et al. (2015) as well as Li and Ingason (2017) experimentally addressed the effect of tunnel cross-section and proposed improved formulas to calculate the critical velocity for metro and road tunnel fires.

In addition, smoke backflow upstream of the fire usually occurs in the early stage of the fire or when the ventilation is insufficient. The backing up length of the ceiling smoke jet is largely determined by the fire size and ventilation velocity, for which considerable efforts have been devoted to characterize and quantify. Hu et al. (2008) analyzed the basic flow characteristics of ceiling smoke spread based on the full-scale experiments and numerical predictions. Focusing on strong plumes, Fan and Yang (2017) investigated the smoke back-layering length in the tunnel where fires are relatively large and proposed some modifications to previously available models based on model-scale burning tests. Salizzoni et al. (2018) utilized the helium-air experiments to quantify the heat loss on the smoke back-layering length.

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Semi-empirical model was proposed to account for the interaction of inertia and buoyancy force. Other important parameters, such as heat release rate (Carvel et al., 2001; Ingason and Li, 2010), environmental wind (Tanaka et al., 2016; Luan et al., 2021), tunnel slope (Atkinson and Wu, 1996; Gwon Hyun et al., 2009; Chow et al., 2015), and fire elevation (Chen and Tang, 2019; Liu et al., 2020), have also been addressed.

However, the aforementioned studies were mostly conducted with fires without any vehicles nearby. Such condition is somewhat idealized and omitted the fact that vehicles and passengers' belongings would be left behind as obstacles due to the overwhelming panic caused by the fire. Furthermore, it should be realized that the presence of obstructions would affect the fire and smoke spread behavior by changing the local wind and thermal conditions. In the last ten years, the major concern associated with blockage effect was related to different topics including the heat release rate, maximum temperature, critical velocity and smoke back-layering length, etc. Kayili et al. (2011) built up a 1/13 scaled model tunnel wherein burning tests were conducted by utilizing wood cribs with different blockage ratios. The coupling effect of blockage ratio and ventilation velocity on heat release rate was revealed. Results declared that heat release rate increases with the blockage ratio and starts to decrease once the ventilation velocity increases exceeding the critical value. Similarly, Wang et al. (2017) measured the mass loss rate of wood crib fires in response to different ventilation velocities and simply established a semi-empirical model to manifest the relationship obtained from data analysis. Based on a series of model-scale experiments, Hu et al. (2013) and Tang et al. (2017) successively investigated the maximum temperature considering different blockage-fire distance and ventilation velocity. Modified models were then proposed by simple data fittings. In the regard of critical velocity and smoke back-layering length, Lee and Tsai (2012) employed three typical blockages queuing in two arrays to quantify the influence of blockage effect on heat release rate of gasoline fires. Besides, critical velocity considering different tunnel height and transverse fire location were also discussed. Investigation of blockage-fire distance was then carried out by Tang et al. (2013). Correlations were proposed by incorporating the normalized blockage-fire distance. Zhang et al. (2016) then carried out a set of model-scale experiments accounting for blockages with a certain cross-section geometry but varying length. The concept of 'virtual fire source' was introduced to modify the previous model in predicting the ceiling temperature decay and smoke back-layering length. Afterwards, emphasis of blockage effect in tunnel fires went to the blockage ratio, which was successively studied by Li et al. (2012), Rojas Alva et al. (2017), Jiang et al. (2018), and Meng et al. (2018b) by the means of numerical or experimental tests, where relationship among the fire size, ventilation velocity, and blockage ratio was discussed in detail.

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Despite of considerable efforts have been paid, to be noticed, no consensus has been achieved by far as most former studies were bounded by limited tunnel shape, fuel type, blockage shape, and ventilation velocity. Currently, three important issues have not been solved yet in the published studies, i.e., 1) Fire burning rate considering the coupling effect of blockage and ventilation are not addressed thoroughly. Lots of previous researches prefer gas fires whose heat release rate is usually deemed as a constant value controlled by the flow meter. There is no doubt that such simplification is acceptable in the laboratory test. However, it may cause some discrepancies in reproducing the real fires wherein combustion of the liquid/solid fuel are very sensitive to the local environment. 2) Most studies are conducted in their pre-designed test beds with different research interest being emphasized, enabling limited fire scenarios being performed and addressed. This may even lead to different findings due to the difference in experiment designs, materials, and apparatus. So far, very few lateral-comparative studies have been carried out in the investigation about blockage effect. 3) The concept of blockage mode in the previous literature is somewhat vague. Blockage effect is represented in different ways while the fire and smoke spreading characteristics possibly behave differently when blockage configuration changes. A clear classification of 'blockage mode' is not defined in the published literature.

To help address these knowledge gaps, the present work analyzed a relatively large body of published experimental data relevant to the blockage effect, covering the fuel burning rate, maximum temperature, critical velocity, and smoke back-layering length. Analysis is anticipated to improve the understanding about blockage and ventilation effect in tunnel fires, which should be assistant to the practical design of tunnel ventilation systems.

2. Experimental data

In the current study, experimental data obtained for analysis are all from the published articles, technique reports, and books. Experiments in the literature are classified into two sets with brief information of experimental set-up embedded in Tables. In Table 1, experiments are carried out from the test beds with longitudinal ventilation only while the coupling effect of ventilation and blockage is then addressed by the experiments shown in Table 2.

Test beds in the previous studies are constructed at multiple scales with different structures and boundaries following the Froude similarity laws. Effectiveness of using such method to simulate the real fire development at reduced scales has been extensively verified by many scholars (Ingason et al., 2015; Chaabat et al., 2020). By holding Froude number F_r as a constant value, conversion of the key parameters are listed as: $\frac{Q_m}{Q_f} = (\frac{L_m}{L_f})^{5/2}$, $T_m = T_f$, $\frac{V_m}{V_f} = (\frac{L_m}{L_f})^{1/2}$, and $\frac{t_m}{t_f} = (\frac{L_m}{L_f})^{1/2}$, where Q represents heat release rate, L denotes length, T means temperature, V is velocity, and t characterizes time. To be noted, uncertainty caused by the difference of experiment settings is inevitable because fuel type, wall material, instruments for measurements, ambient parameters are varying among different studies. The reliability of each data set was described in the original publication and not incorporated in the current work.

3. Results and discussion

3.1 Heat release rate

Heat release rate Q is a representative parameter to characterize the fire disaster in tunnels and is sensitive to the environmental conditions such as wind and temperature (Hu, 2017; Yao et al., 2019). The calculation of heat release rate is largely determined by fuel burning rate referring to

$$Q = \chi \cdot \Delta H_c \cdot \dot{m} \qquad (1)$$

where χ is the combustion efficiency, ΔH_c is the specify heat of combustion, and $\dot{m}$ is fuel burning rate. In this section, discussion of ventilation and blockage effect on fuel burning rate or heat release rate will focus on the pool fires and wood crib fires only as burning rate of the gas fire is usually prescribed by the flow meter and is not sensitive to the ventilation and blockage effect.

In the laboratory experiments, hydrocarbon fuels like methanol, alcohol, gasoline, and heptane and solid fuels such as wood crib are often utilized to simulate the real fires. Figure 1 and Figure 2 exhibit the variation of fuel burning rate/heat release rate in the longitudinal-ventilated tunnel without blockage. To assist the review of literature data, methanol pool fires in Figure 1 are classified into three types depending on the pool dimension as the small, medium, and large fires. To be noted, the purpose of this classification is for data exhibition only and is not considering the scale effect which may lead to different burning regimes (Hu, 2017). Discussion related to this regard will be given later associated with the specific problem (referring to the discussion of Figure 3).

As shown in Figure 1, for a certain pool size, measurements from Roh et al. (2007), Hu et al. (2009), Tian et al. (2020), and Wang et al. (2021) denote that fuel burning rate/heat release rate of methanol pool fires firstly decreases and then increases when the longitudinal ventilation velocity increases. The turning point appears roughly at $V = 1.6$ m/s in Figure (1-a) and (1-b), and $V = 2.4$ m/s in Figure (1-c). Both the decline and increment of burning rate/heat release rate caused by the increase of ventilation velocity are significant. For example, for all the pool

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fires with various pool dimensions, fuel burning rate in Figure 1-(b) drops by more than a half when the wind velocity increases from 0.0 m/s to 1.6 m/s and then increases doubled when the velocity increases up to 3.2 m/s. This is quite similar with Yao et al. (2019)'s finding that for the methanol pool fires with diameter b_f respectively equal to 0.15 m and 0.46 m, fuel burning rate drops by 40% when the wind velocity increases from 0.0 m/s to 1.5 m/s. The reason behind can be explained by the change of heat transfer mechanism. When the ventilation velocity first increases, cooling effect of the wind flow, being the dominated force, results in the decrease of radiative heat feedback from the flame. Meanwhile, decrease of the surrounding temperature enables the evaporation rate at fuel surface to decrease. However, the further increasing velocity of the wind flow will result in strong deflection of the flame where the leeward side of pool rims are extensively heated. As a result, the conductive heat transfer from the pool rims to the fuel becomes more intensive, thus increases the fuel burning rate. Furthermore, when the wind velocity is relatively strong, the convection boundary layer above the fuel surface will be dominated by the wind forced convection boundary layer, leading to the increase of convective heat feedback at fuel surface (Hu, 2017). Correspondingly, fuel burning rate increases. Moreover, it is notable that burning rate (per unite area) of the small methanol pool fires decreases as pool diameter increases when ventilation velocity V approximately exceeds 0.8 m/s, e.g., burning rate of the 5 cm × 5 cm fire is nearly three times higher than that of the 15 cm × 15 cm fire as shown in Figure 1-(a) and burning rate of the 42.4 cm × 28.2 cm fire is nearly 0.003 kg/m^2·s higher than that of the 84.2 cm × 59.2 cm fire as plotted in Figure 1-(c). This is mainly due to the increasing radiative and convective heat feedback caused by the flame deflection. Previously, investigation about flame deflection suggests that the inclined angle of fire plume has strong relationship with ventilation velocity V and pool diameter b_f. In terms of open fires, Raj et al. (1979) proposed the following formula to calculate the tilted angle of fire plume

$$sin\theta = \begin{cases} 1, & V' \leq 0.19 \\ (5.26 \cdot V')^{-0.5}, & V' > 0.19 \end{cases} \tag{2}$$

with $V' = V/(\frac{Q_c g}{b_f \rho_a C_p T_a})$, where V' is the character ventilation velocity, b_f is the fire radius, and θ is the inclined angle. By conducting a set of burning tests in model-scaled tunnels, Li and Ingason (2012b) indicates the flame tilted angle in a longitudinally ventilated tunnel can be generated as

$$sin\theta = \begin{cases} 1, & V' \leq 0.19 \\ (5.26 \cdot V')^{-3/5}, & V' > 0.19\ and\ Q^* \leq 0.15 \\ 0.5H^{1/2}(b_f V)^{-1/5}, & V' > 0.19\ and\ Q^* > 0.15 \end{cases} \tag{3}$$

From the above equations, it can be seen that for a certain ventilation velocity, the decrease of pool diameter will result in the increase of flame inclination. In other words, fuel surface and pool rims of the pool fire with small diameter will presumably receive more intensively radiative and convective heat feedback. Both the heated pool rims and increasing temperature of fuel surface caused by the enhanced heat feedback is very likely to result in a higher burning rate. Apart from methanol pool fires in Figure 1, similar varying tendency can also be observed in ethanol and gasoline fires as exhibited in Figure 2.

Figure 2 further plots the variation of burning rate from other fuels, e.g., acetone, gasoline, ethanol, and heptane. In general, results indicate significant increment of fuel burning rate when the ventilation velocity increases from 0.0 m/s to roughly 3.0 m/s (except the measurements from Shafee et al. (2017)). For example, as shown in Figure 2-(c), when the wind velocity increases up to 3.0 m/s, burning rate of the 4 cm × 4 cm ethanol pool fire increases to more than triple of that at the quiescent state ($V = 0.0$ m/s). This seems to be contradictory from the conclusion that we obtained from the methanol pool fires as shown in Figure 1. However, such differences are likely to the differences in the proportion of heat transfer due to the conduction, convection, and radiation associated with different fuel types. Besides, the mechanism of heat feedback to the pool fire in the presence of the wind is also very complicated. By far, different conclusions can be found in the previous literature. For example, study of Blinov and Khudyakov (1961) concluded that the burning rate of pool fires proportionally increases in response to the increase of ventilation velocity. However, measurements from Welker and Sliepcevich (1966) implied that the burning rate of acetone, n-hexane, cyclohexane, and benzene pool fires decreases with the increase of the ventilation velocity while the burning rate of methanol pool fires almost maintains at a constant value when the wind velocity varies from approximately 0.30 m/s to 1.50 m/s. It can be found out that even though the fuel type is kept the same, i.e., the methanol pool fires, different conclusions about burning rate can still be drawn by different researchers, like Welker and Sliepcevich (1966) and Hu et al. (2009).

Figure 3 displays the fuel burning rate of the wood crib fires and pool fires burned with blockage. The plotted data in Figure 3-(a) indicate that the burning rate of wood crib fires generally increases with the longitudinal ventilation velocity, even though different blockages are utilized. For the pool fires burned with the same blockage, Figure 3-(b) implies that fuel burning rate shows opposite variation when pool size varies. As ventilation velocity increases from 3.6 m/s to 4.2 m/s, fuel burning rate of the 0.5 m^2 pool fire slightly decreases while burning rate of the 1.0 m^2 pool fire firstly increases and then decreases. This may attribute to the scale effect, i.e., the pool size b_f, which leads to different heat feedback regimes. In the presence of wind, variation of heat feedback possibly becomes more complicated as thermal condition nearby the fire is significantly affected by ventilation effect (Hu, 2017). The scale effect was earlier investigated by Babrauskas (1983), who concluded four typical regions, i.e., (I) the laminar flames with $b_f < 0.05$ m to be dominated by convection, (II) turbulent flames with $0.05 \leq b_f < 0.20$ m to be dominated by convection, (III) optically-thin flames with $0.20 \leq b_f < 1.0$ m to be dominated by radiation, and (IV) optically-thick flames with $b_f \geq 1.0$ m to be dominated by radiation. Clearly, the two pool fires in Kang et al. (2019)'s study possibly belong to different regions, leading to the different responses to the wind.

To be noted, due to the lack of data, detailed analysis related to the coupling effect of blockage ratio and longitudinal ventilation affect fuel burning rate is not addressed in the current work. There is, however, essential need for such gaps to be addressed in future research.

3.2 The maximum temperature

Prediction of the maximum temperature in tunnels is a very practical issue as it is strongly connected to how accurate the fire risk can be estimated. Through a set of burning tests in five tunnels with different aspect ratios, Kurioka et al. (2003) established an empirical formula, i.e., Eq.(4), to calculate the maximum temperature in longitudinal-ventilated tunnels as

$$\frac{\Delta T_{max}}{T_a} = \gamma \left(\frac{Q^{*2/3}}{F_r{}^{1/3}} \right)^{\varepsilon} \tag{4-a}$$

with

$$Q^* = \frac{Q}{\rho_a C_p T_a \sqrt{g} H_{ef}{}^{5/2}} \tag{4-b}$$

$$F_r = V^2 / g H_{ef} \tag{4-c}$$

$$\begin{cases} Q^{*2/3}/F_r{}^{1/3} < 1.35, & \gamma = 1.77, \varepsilon = 6/5 \\ Q^{*2/3}/F_r{}^{1/3} \geq 1.35, & \gamma = 2.54, \varepsilon = 0 \end{cases} \tag{4-d}$$

where T_a and ΔT_{max} are respectively the ambient temperature and maximum temperature rise, Q^* is dimensionless heat release rate, ρ_a and C_p are air density and heat capacity, H_{ef} denotes effective tunnel height, g represents gravity, γ and ε are fitting coefficients determined by experiments. However, one shortcoming of Eq. (4) is that the predicted value may approach infinite when the ventilation velocity is very low. Based on dimensionless analysis and measurements from multi-scale experiments, Li and Ingason (2012a) proposed a two-piece correlation to calculate the maximum temperature as

$$\Delta T_{max} = \begin{cases} DTR1 = 17.5\frac{Q^{2/3}}{{H_{ef}}^{5/3}}, & V' \leq 0.19 \\ DTR2 = \frac{Q}{V{b_f}^{1/3}{H_{ef}}^{5/3}}, & V' > 0.19 \end{cases} \tag{5-a}$$

with

$$\Delta T_{max} = \begin{cases} DTR1, & DTR1 \leq 1350 \\ 1350, & DTR1 > 1350 \end{cases} when\ V' \leq 0.19 \tag{5-b}$$

and

$$\Delta T_{max} = \begin{cases} DTR2, & DTR2 \leq 1350 \\ 1350, & DTR2 > 1350 \end{cases} when\ V' > 0.19 \tag{5-c}$$

The constant value in Eq. (5-b) and (5-c) represents the maximal value of the ceiling temperature rise, or namely the upper limit, which largely depends on the fuel type and wall boundaries and therefore usually varies in different reports, e.g., 770 ℃ in Kurioka et al. (2003), 850 ℃ in Ji et al. (2015), 1073 ℃ in Chen et al. (2019), and 1350 ℃ in Li and Ingason (2012a).

Figure 4 exhibits the comparison between the prediction results by using Eq. (4)-(5) and literature data from Table 1. The relatively good agreement between the literature data and correlations proposed by Kurioka et al. (2003) and Li and Ingason (2012a) indicate reliable prediction results for the fires burned without blockage. When the blockage effect is further considered, however, the prediction may be no longer effective as the environmental condition at the vicinity of the fire change in two typical ways, i.e., the wind condition and heat feedback. In many previous investigation (Jiang et al., 2018; Meng et al., 2018b), blockage ratio $\varphi = \frac{A_b}{A_t}$ is adopted to quantify the influence caused by the vehicular blockage, where A_b and A_t are respectively the cross-section area of blockage and tunnel. The wind condition is associated with the longitudinal ventilation. When there is no blockage inside the tunnel or the blockage locates at the leeward side of the fire, velocity of the ventilated airflow passing across the fire, namely V_{local}, is equal with the longitudinal ventilated velocity V. Once the blockage is placed at the upwind side of the fire, V_{local} is then calculated following the continuity equation as

$$V_{local} = V \cdot \frac{A_t}{A_t - A_b} = V \cdot \frac{1}{1-\varphi} \tag{6}$$

The varying wind condition enables the thermal condition near the fire to change, as well as the ceiling smoke propagation. Furthermore, in the presence of the wind, the fire source is likely to receive much more heat feedback from the surfaces of blockage, which usually leads to a different thermal behavior.

Before the analysis of blockage effect, three typical blockage modes are extracted based on the survey of previous literature. As shown in Figure 5, the Type-A blockage represents the fire scenario where fires are burned with blockage nearby. This is likely to happen in the tunnel where traffic congestion frequently occurs. To be clarified, only the condition that the blockage in Type-A being placed upstream of the fire is concerned because it has been verified by Hu et al. (2013) that the blockage placed downstream of the fire exerts almost no contribution on both the ceiling temperature and smoke spread. The Type-B blockage is very common to see in the real fires, i.e., the vehicle itself burns as blockage. The Type-C blockage is a typical way of model simplification utilized in some experimental studies, like Oka and Atkinson (1995). In the following, quantitative analysis with respect to the maximum temperature, critical velocity, and back-layering length will be carried out with these three typical blockage modes being addressed.

In Figure 6 and 7, literature data covering Type-A and B blockages are respectively compared with Eq. (4) and (5) proposed by Kurioka et al. (2003) and Li and Ingason (2012a). To be noted, analysis of the maximum temperature will not cover Type-C mode as very few experimental data can be obtained from the previous literature. As for the Type-A mode where fires burn with different upstream blockage-fire distance L_{bf}, the predicted results by Kurioka et al. (2003) and Li and Ingason (2012a) both show reasonably good agreement. Even though deviation between the predicted lines and literature data still exists, such as Meng et al. (2018b) in Figure 6-(a) and Zhu et al. (2017) in Figure 7-(a), it is reasonable to use Eq. (4) and (5) to predict the maximum temperature in Type-A mode since the overall agreement is acceptable. Such deviation is rational because both blockage ratio φ and blockage-fire distance L_{bf} may have certain influence on the flow filed and thermal condition nearby the fire. The flow streamlines and temperature contours in the research by Meng et al. (2018a) has provided some explanations for this issue. In Meng's study, area between the fire and blockage can be simply known as the 'recirculation region' where flow velocity is relatively lower due to the flow vortex. With the increase of blockage ratio, the total length of the 'recirculation region' increases and vortex becomes more intensive. In the Type-A mode, plume entrainment and thermal condition near the fire is inevitably affected by the increases of the blockage ratio φ and blockage-fire distance L_{bf}, resulting the variation of maximum temperature as plotted here. However, such discrepancy is still within an acceptable range and will not challenge the credibility of Eq. (4) and (5). Similar findings were also reported by Hu et al. (2013) where the maximum temperature difference caused by the blockage-fire distance L_{bf} compared to that without blockage is less than 12%.

As shown in Figure 6-(b) and Figure 7-(b), the literature data from Kayili et al. (2011) poorly match the prediction results of Eq. (4)-(5) when different blockage ratios are applied in Type-B mode. The reason behind is that both the variation of wind and heat feedback in this situation become more dependent to the blockage (or the fire itself). More concretely, when the fire burns in Type-A mode, ventilation effect is not directly exerted to the fire source due to the blockage but will affect the combustion by altering the wind and thermal environment near the fire. In this situation, the fire receives heat feedback from two typical ways, i.e., the blockage and the rim walls of tunnel structure. The former one varies when the blockage ratio or blockage-fire distance L_{bf} changes while the later one is independent to the blockage ratio as the fire-wall distance is determined in advance. On the contrary, effect of wind and heat feedback are directly exerted to the fire source in Type-B mode. Heat feedback in Type-B mode is strongly affected by the blockage ratio because fire-wall distance varies when the blockage dimension changes. Figure 6-(c) and Figure 7-(c) reveal another difference between the prediction results and literature data, i.e., the upper limit of maximum temperature. As illustrated before, the determination of upper limit relies on several vital parameters, like fuel type and tunnel structure, which results in the controversies in this regard. Since Li and Ingason (2012a)'s research was carried out based on many large-scale experiments, their recommended value, i.e., 1350 ℃, is adopted in the present work.

Since the estimation of maximum temperature in Type-B mode remains problem by using Eq. (4) and (5), modified formulae are proposed to correlate the measurements from Kayili et al. (2011). As shown in Figure 8 and 9, by utilizing the local velocity V_{local} to account for the blockage effect, modified correlations are derived through simple data fitting as

$$\frac{\Delta T_{max}}{T_a} = 0.84\left(\frac{Q^{*2/3}}{{F_r'}^{1/3}}\right)^{0.295} \tag{7-a}$$

with

$$F_r' = {V_{local}}^2/gH_{ef} \tag{7-b}$$

and

$$\Delta T_{max} = \begin{cases} \frac{Q}{V_{local}{b_f}^{1/3}{H_{ef}}^{5/3}}, & \frac{Q}{V_{local}{b_f}^{1/3}{H_{ef}}^{5/3}} \leq 1350 \\ 1350, & \frac{Q}{V_{local}{b_f}^{1/3}{H_{ef}}^{5/3}} > 1350 \end{cases} \quad when\, V' > 0.19 \tag{8}$$

To be noted, the upper limit for Eq. (7) and the first piece of Eq. (8), i.e., $V' \leq 0.19$, are not given in the revised correlations as they are out of the measuring range in Kayili et al. (2011). Research related to this regard is worthy to be carried out in the future. Besides, Eq. (7) should be carefully used when the ventilation velocity is very low as it may approach infinity.

3.3 Critical velocity and Back-layering length

Control of smoke back-layering length has been extensively investigated by many scholars in the past few decades. Thomas (1958) earlier proposed the following correlation to calculate the back-layering length in a longitudinal-ventilated tunnel:

$$l^* = \frac{L_{sb}}{H_t} \propto \frac{gH_tQ}{\rho_a T_s C_p V^3 A_t} \tag{9}$$

where L_{sb} represents the smoke back-layering length, H_t is tunnel height, T_s denotes smoke temperature. Considering the effect of tunnel cross-section, Wu and Bakar (2000) found good agreement between the dimensionless critical velocity $\overline{V_c}$ and heat release rate $\overline{Q^*}$ by using the hydraulic tunnel height $\overline{H_t}$ in the following correlation

$$\overline{V_c^*} = \begin{cases} 0.40[0.20]^{-1/3}[\overline{Q^*}^{1/3}], & \overline{Q^*} \leq 0.20 \\ 0.40, & \overline{Q^*} > 0.20 \end{cases} \tag{10-a}$$

with

$$\overline{V_c^*} = \frac{V_c}{\sqrt{g\,\overline{H_t}}} \tag{10-b}$$

and

$$\overline{Q^*} = \frac{Q}{\rho_a C_p T_a g^{1/2} \overline{H_t}^{5/2}} \tag{10-c}$$

Deberteix (2000) obtained similar conclusion from the scaled model tests, where measurements led to the correlation between Richardson number and dimensionless smoke back-layering length being expressed as

$$l^* = 7.5\,(Ri^{1/3} - 1) \tag{11}$$

where Richardson number is expressed as $Ri = \frac{T_s - T_a}{T_a} \cdot \frac{gH_t}{V^2}$. Based on the dimensionless analysis and a set of reduced scale experiments, Li et al. (2010) proposed the following formulae to calculate the back-layering length and critical velocity considering different fire sizes

$$V_c^* = \begin{cases} 0.81{Q^*}^{1/3}, & Q^* \leq 0.15 \\ 0.43, & Q^* > 0.15 \end{cases} \tag{12}$$

and

$$l^* = \begin{cases} 18.5\ln\left(0.81{Q^*}^{1/3}/V^*\right), & Q^* \leq 0.15 \\ 18.5\ln(0.43/V^*), & Q^* > 0.15 \end{cases} \tag{13-a}$$

where $V_c^* = \frac{V_c}{\sqrt{gH_t}}$. With term ${Q^*}^{1/3}/V^*$ equal to one-third power of Richardson number, Eq. (13-a) is thus re-written as:

$$l^* = \begin{cases} 18.5\ln\left(0.81Ri^{1/3}\right) \quad , & Q^* \le 0.15 \\ 18.5\ln(0.43/V^*) \quad , & Q^* > 0.15 \end{cases} \tag{13-b}$$

For the fire burns with a blockage ($\varphi = 0.20$), Li et al. (2010) suggested the critical velocity and smoke back-layering length could be estimated as

$$V_c^* = \begin{cases} 0.63{Q^*}^{1/3}, & Q^* \le 0.15 \\ 0.33, & Q^* > 0.15 \end{cases} \tag{14}$$

$$l^* = \begin{cases} 18.5\ln\left(0.63Ri^{1/3}\right) \quad , & Q^* \le 0.15 \\ 18.5\ln(0.33/V^*) \quad , & Q^* > 0.15 \end{cases} \tag{15}$$

Weng et al. (2015) proposed the following equation for the smoke back-layering length in metro tunnels through model-scale experiments and simulations:

$$l^* = 7.13 \cdot \ln\left(Q^*/{V^*}^3\right) - 4.36 \tag{16}$$

It should be noticed that the aforementioned studies were mostly conducted in longitudinal-ventilated tunnels without blockage. Effectiveness of the above correlations cannot be guaranteed if they are further applied in the situation where fires burn with blockage nearby. Recently, even though many researchers (Tang et al., 2017; Shafee and Yozgatligil, 2018; Han et al., 2021a) have reported the importance of blockage effect, further investigation is still needed because very few studies focused on the blockage effect by simultaneously considering three blockage modes.

Figure 10 and Figure 11 respectively display the variation of smoke back-layering length l^* and critical velocity V_c^* in longitudinal-ventilated tunnels without blockage. As shown in Figure 10, Measurements from Tanaka et al. (2018), Liu et al. (2020), and Peng et al. (2020) indicate that smoke back-layering length decreases as ventilation velocity increases and is dependent to the heat release rate. Figure 11 plots the literature data along with the correlations proposed by Wu and Bakar (2000) and Li et al. (2010). Results denote that the critical velocity firstly increases and then maintains at a constant value. This implies that by increasing the ventilated velocity up to a certain level, smoke spread upstream of the fire can be entirely eliminated. In the meanwhile, it should be also noticed that value of the upper limit usually varies in different studies, i.e., V_c^*equals to 0.40 in Wu and Bakar (2000) and 0.43 in Li et al. (2010). A simple formula to correlate the previous measurements from Roh et al. (2007), Li et al. (2010), Tanaka et al. (2018), Liu et al. (2020), and Peng et al. (2020) yields the fitted equation as

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$$V_c^* = \begin{cases} 1.08{Q^*}^{1/3}, & Q^* \leq 0.15 \\ 0.58, & Q^* > 0.15 \end{cases} \quad (17)$$

Thereafter, measurements of smoke back-layering length are plotted in Figure 12 along with Eq. (11), (13), and (16) respectively proposed by Deberteix (2000), Li et al. (2010), and Weng et al. (2015). Results indicate that the previous correlations underestimate the smoke back-layering length. In the same way, a correlation to fit the previous measurements is then given as

$$\frac{L_{sb}}{H_t} = 15.92\, ln\left(\frac{{Q^*}^{1/3}}{V^*}\right) + 1.19 = 15.92\, ln\left(1.08\frac{{Q^*}^{1/3}}{V^*}\right) \quad (18)$$

Combined with Eq. (17), smoke back-layering length in a longitudinally ventilated tunnel without blockage can be estimated by the following equation

$$l^* = \begin{cases} 15.92 \ln\left(1.08{Q^*}^{1/3}/V^*\right) & , \quad Q^* \leq 0.15 \\ 15.92 \ln(0.58/V^*) & , \quad Q^* > 0.15 \end{cases} \quad (19)$$

Figure 13 shows measurements of smoke back-layering length considering different blockages in blockage Type-A mode. Results of Figure 13-(a) denote huge difference between the previous correlations and measurements from Zhang et al. (2016), Zhu et al. (2017), and Meng et al. (2018b). The reason behind is possibly due to the variation of wind and thermal condition caused by the blockage, which has been explained in the former section. Herein, V_{local} is utilized to modify the previous correlations. The fitting results, as well as the comparison with previous correlations are shown in Figure 13-(b). The empirical correlation to fit the previous measurements is expressed as

$$l^* = 9.20\, ln\left(1.38{Q^*}^{1/3}/V_{local}^*\right) \quad (20)$$

To be noted, even though the critical parameter, i.e., blockage-fire distance L_{bf}, is different in Zhang et al. (2016), Zhu et al. (2017), and Meng et al. (2018b), where L_{bf} =0 m in Zhang et al. (2016) and Zhu et al. (2017), and L_{bf} =4 m in Meng et al. (2018b), by using V_{local}^* as the modification factor the plotted data exhibited in Figure 13-(b) denote insignificant difference. This is likely because compared with blockage ratio, blockage-fire distance L_{bf} may not be the dominated influencing factor. Similar results can also be observed from the figures reported by Tang et al. (2013) where variation of dimensionless smoke back-layering length is limited when the blockage-fire distance L_{bf} varies. Moreover, only the measurements associated with Type-A mode are analyzed here as very few experimental data related to the other two types can be obtained from the previous literature.

Measurements of critical velocity involving three type blockages are further plotted in

Figure 14-(a) along with Eq. (10) and (14) proposed by Wu and Bakar (2000) and Li et al. (2010), presenting good agreement. However, if V^* in Eq. (10) and (14) is directly replaced by V^*_{local}, results denote that those measurements are relatively higher than the predicted values but are well matched by the calculation result through the following equation

$$V^*_{c,local} = \begin{cases} 0.85Q^{*1/3}, & Q^* \leq 0.22 \\ 0.51, & Q^* > 0.22 \end{cases} \tag{21}$$

It is interesting to find out that by assuming l^* in Eq. (20) to be zero, value of the critical velocity for Type-A mode $V^*_{c,local}$ should be equal to $1.38Q^{*1/3}$. This is obviously higher than the prediction of Eq. (21) where $V^*_{c,local} = 0.85Q^{*1/3}$ for the fire with $Q^* \leq 0.22$. However, this is likely because these two fitted correlations are determined by measurements produced by different experimental settings and boundaries. After all, limitations of the present work are given here as 1) experimental data of critical velocity in blockage Type-A mode account for the fire scenario where blockage-fire distance $L_{bf} = 0$ m only, critical velocity affected by varying blockage-fire distance L_{bf} is not covered here, 2) divergency still remains in the prediction of critical velocity and smoke back-layering length in the longitudinal-ventilated tunnel with blockages. Knowledge gap related to the aforementioned issues are still calling for more investigation in the future work.

4. Conclusions

A wide range of published experimental measurements associated with blockage effect in longitudinal-ventilated tunnels have been collected. Quantitative analysis has been carried out to address the blockage and ventilation effects on fuel burning rate, maximum temperature, critical velocity, and smoke back-layering length. Analysis has led to modified correlations for the maximum temperature, critical velocity, and smoke back-layering length in tunnels accounting for the coupling effect of blockage and ventilation effect. Key findings of the current work are summarized as follows.

1) Pool fires and wood crib fires are sensitive to ventilation effect. For the measurements considered in the present research, as longitudinal ventilation velocity increases, fuel burning rate of the methanol pool fires firstly increases and then decreases due to the change of heat transfer mechanism. The burning rate of the other fuels, including acetone, gasoline, ethanol, heptane, and wood crib, increases monotonically with the wind velocity.

2) The maximum temperature in a longitudinal-ventilated tunnel can be well predicted by the correlations of Kurioka et al. (2003) and Li and Ingason (2012a) when there is no blockage

inside. However, both correlations led to relatively large discrepancies with the measurements in the cases with blockage. The present study modified the previous correlations by considering three typical blockage types. The modified formulae achieved relatively good agreement with the literature data.

3) Smoke back-layering length decreases with the increase of ventilation velocity and is dependent to the heat release rate. The modified correlations for critical velocity and smoke back-layering length in tunnels without blockage are found to agree well with the literature data. For the tunnel with blockage, blockage ratio is incorporated to modify the previous correlations. However, the modified correlations only led to limited improvement and discrepancy still exists between the predictions obtained from different literature data. Such discrepancy highlights the need for further laboratory tests with systematically varied blockage arrangement.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by Graduate Scientific Research and Innovation Foundation of Chongqing, China (Grant No. CYB20029), Chongqing Science and Technology Commission (Grant No. cstc2019jscx-msxmX0243) and Chongqing Construction Science and Technology Planning Project 459 (Grant No. 2019(1-5-5)).

Jiaqiang Han would also like to acknowledge the financial support of China Scholarship Council under the Program for Ph.D. Student Overseas Study Scholarship 2020 (Grant No. 202006050098), which facilitates his study at Warwick Fire, School of Engineering at University of Warwick.

Table headings

Table 1. Summary of burning tests in literature (without blockage).

Table 2. Summary of burning tests in literature (with blockages).

Figure Captions

Figure 1. Burning rates of methanol pool fires versus longitudinal ventilation velocity

(without blockage): (a) Small size fires; (b) Medium size fires; (c) Large size fires.

Figure 2. Burning rates of pool fires versus longitudinal ventilation velocity (without blockage): (a) Acetone; (b) Gasoline; (c) Ethanol; (d) Heptane.

Figure 3. Burning rates versus longitudinal ventilation velocity (with blockage): (a) Wood crib fires; (b) Mixture of diesel and gasoline fires.

Figure 4. Maximum temperatures in tunnels (without blockage).

Figure 5. Typical modes of blockages in the literature.

Figure 6. Maximum temperatures in tunnels compared with correlation by Kurioka et al. (2003) (with different blockages).

Figure 7. Maximum temperatures in tunnels compared with correlation by Li and Ingason (2012a) (with different blockages).

Figure 8. Modified correlation via measurements from Kayili et al. (2011) [Based on Eq. (4)].

Figure 9. Modified correlations via measurements from Kayili et al. (2011) [Based on Eq. (5)].

Figure 10. Relationship between longitudinal velocity and back-layering length

(Without Blockage).

Figure 11. Prediction of critical velocity (Without Blockage).

Figure 12. Prediction of smoke back-layering length (Without Blockage).

Figure 13. Prediction of smoke back-layering length (With Blockage, Type A).

Figure 14. Prediction of critical velocity (With Blockage).

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