Effect of ceiling extraction on the smoke spreading characteristics and temperature profiles in a tunnel with one closed end

Jiaqiang Han[a,b]; Pengqiang Geng[a]; Zihao Wang[c]; Yuhan Lu[a]; Fei Wang[a]; Jennifer Wen[b*]; Fang Liu[a,d,e**]

a School of Civil Engineering, Chongqing University, Chongqing, 400045, P.R. China;

b School of Engineering, University of Warwick, CV4 7AL, Coventry, UK

c College of Environment and Ecology, Chongqing University, Chongqing, 400045, P.R. China;

d Key Laboratory of New Technology for Construction of Cities in Mountain Area of Ministry of Education (Chongqing University), Chongqing, 400045, P.R. China;

e Joint International Research Laboratory of Green Buildings & Built Environments, Chongqing, 400045, P.R. China;

*Corresponding author:

Jennifer Wen: jennifer.wen@warwick.ac.uk , University of Warwick, Coventry, CV4 7AL, UK

Fang Liu: drliufang@126.com , Chongqing University, Shapingba District, 400045, P.R. China

Abstract

A series of fire tests in a 1/15 scaled-model tunnel with one closed end have been conducted. Analysis was carried out to explore temperature distribution and smoke propagation under the influence of ceiling extraction system. Five different heat release rates, three dimensions of exhaust outlet, and numerous extraction rates were considered. Experimental results led to some interesting findings about the relationships between smoke extraction rate, fuel mass burning rate, and ceiling temperature. Two distinctive ceiling temperature regions were identified according to their different responses to smoke extraction rate, i.e., ceiling temperature decay between the fire and outlet was almost independent of smoke extraction rate while temperature upstream of the outlet decreased sharply with the increase of smoke extraction rate. Analysis was also conducted about smoke back-layering length, revealing its strong dependence on heat release rate and induced air velocity. Based on the experimental results and dimensional analysis, three empirical formulas were proposed to capture ceiling temperature decay and smoke back-layering length for tunnels with one closed end utilizing ceiling smoke extraction.

***Keywords*:** Maximum temperature; Temperature decay; Back-layering length; Ceiling extraction; Closed end; Tunnel fire

Nomenclature

Nomenclature	
Q	Heat release rate (kW)
Q^*	Dimensionless heat release rate
V	Velocity (m/s)
V^*	Dimensionless velocity
l	Length (m)
l^*	Dimensionless back-layering length
T	Temperature (℃)
ΔT	Temperature rise (K)
H	Tunnel height (m)
D	Diameter (mm)
d	Distance from the fire to end wall (m)
t	Time (s)
ρ	Ambient air density (kg/m^3)
C_p	Specific heat of ambient air (kJ/kg·K)
g	Gravity acceleration (m/s^2)
$\dot{m}$	Burning rate (g/s)
x	Measuring point upstream of the fire (m)
x_0	Reference point
A	Area (m^2)
Subscript	
m	Model scale
f	Full scale
a	Ambient value
s	Smoke
up	Upstream of the fire
ht	Hydraulic height
ef	Effective height
ex	Extraction
in	Induced velocity
out	Outlet
max	Maximal value
$down$	Downstream of the fire
$virtual$	Virtual fire source
Greek letters	
φ	Temperature attenuation coefficient Equation (5)
σ	Heat transfer coefficient (W/ m^2·K)
α	Coefficient in Equation (11)
β	Coefficient in Equation (11)

1. Introduction

Tunnels are important transport infrastructure in the urban traffic system to facilitate transport through mountains and sea, and to release land traffic pressure by fully utilizing the underground spaces. They can also support the installation of gas transmission pipelines, electricity supply lines, and many other important facilities in city engineering. The rapid development of urban transportation in recent years has resulted in significant increase of tunnel construction in China. Such growing trend has brought new challenges owing to a variety of shapes and designs in which these tunnels are constructed, as well as the demand to be compatible with the local landform. In the past few years, the tunnel designed with a closed end, or a similar structure, gradually becomes common as tunnel-style depots (Han et al., 2020; Wang et al., 2021), utility tunnels (Liu et al., 2019; Gao et al., 2021), tunnels under construction (DeJoseph, 2004; Mehaddi et al., 2020), subway stations (Ji et al., 2011; Weng et al., 2014), and corridors (Li et al., 2011a; Ishikawa et al., 2020), etc. There is an increasing concern about the fire risk inside such type of tunnels with one closed end.

Tunnel fire has attracted considerable attention (Atkinson and Wu, 1996; Ura et al., 2014; Shi et al., 2020; Yu et al., 2020) owing to its potentially high consequences in human casualties, property losses, and structure damage. Comparing to traditional tunnels with two opened portals, smoke and heat released from the fire can be discharged through one opened portal only in a tunnel with one closed end, resulting in massive heat and smoke gathering near the closed end wall with potentially high risk of tunnel structure damage. Moreover, human evacuation routes in such tunnels are in the same direction as smoke movement. Consequently, passengers are likely to be exposed to the hot and suffocating gases, presenting great challenges. Hence, effective fire prevention and protection as well as smoke control strategies are of great importance.

For effective smoke control in tunnels, mechanical ventilation systems have received growing attention due to their reliability. Both longitudinal ventilation (Li et al., 2010; Ingason et al., 2015b; Shi et al., 2021) and point extraction (Li et al., 2016; Jiang et al., 2018a) systems are widely used. Longitudinal ventilation is generally more popular, due to its relatively low investment and fast installation. In the event of a fire, such system produces a steady airflow along longitudinal direction to shorten the back-layering length and to create a smoke-free region upstream of the fire (Fan and Yang, 2017). In the meantime, heat and suffocating gases are expelled via the downstream opening. Such approach, however, is likely to lose its effectiveness in a tunnel with one closed portal.

When the ceiling extraction system is activated in case of a fire, smoke will be directly exhausted via the outlet. As a result, smoke layer thickness becomes thinner and the risk of smoke inhalation is reduced. Furthermore, if the extraction effect is enough strong, longitudinal smoke spreading will be confined by the induced airflow. Such advantages indicate that ceiling extraction system is perhaps less limited by the tunnel structure than the longitudinal type and is likely to be more effective in tunnels with one closed end. An important design parameter in the ceiling extraction system is the minimum airflow velocity to prevent smoke propagating after the last activated exhaust vent. This was defined as confinement velocity by Vauquelin and Telle (2005), who estimate the confinement velocity when smoke back-layering length was four times the value of tunnel height. Jiang et al. (2018b) further explored the influence of outlet area and heat release rate on the induced air velocity and proposed a new formula to predict the induced air velocity in a tunnel with two-point ceiling extraction system. As for temperature profiles affected by the ceiling extraction system, Tang et al. (Tang et al., 2017; Tang et al., 2018a; Tang et al., 2018b; Tang et al., 2018c) successively investigated the temperature decay, maximum temperature, and air entrainment characteristics by conducting numerous experimental tests in scaled model tunnels. They derived and modified the temperature attenuation coefficient and revealed the relationship between entrainment coefficient and Richardson number.

The aforementioned studies were predominately conducted in a traditional tunnel with two opened portals and mechanical ventilation. Ceiling extraction applied in a tunnel with one closed end has hitherto received relatively less attention. In such situation, the amount of smoke spreading towards upstream more than doubles, resulting in changes of temperature profiles and smoke propagating patterns. Furthermore, despite the investigation about optimal ventilation strategy (Yu et al., 2018; Long et al., 2020) and exhaust efficiency (Yi et al., 2015; Tan et al., 2020) of extraction systems, there are still some knowledge gaps about how the smoke spreads and temperature distributes in a tunnel with one closed end regarding the extraction effect. The present study hence conducted a series of burning tests in a 1/15 scaled model tunnel utilizing five heat release rates, three outlet dimensions and numerous extraction rates to reveal the basic thermal characteristics under such fire scenarios. The novelties of this work are: 1) revealing the smoke extraction effect on pool fire burning rate and the maximum temperature in a tunnel with one closed end; 2) Defining two different ceiling regions to characterize the corresponding variation of thermal responses to the extraction effect and proposed corresponding formulas to calculate ceiling temperatures; 3) Introducing the concept of 'idealized' induced air velocity to quantify the impact of extraction effect on smoke back-layering length.

The remainder of this paper is organized as: Section 2 gives a brief introduction of the test bed and measuring apparatus. Section 3 conducts quantified analysis to explore the influence of smoke extraction on the maximum temperature, ceiling temperature distribution, and smoke back-layering length. Finally, the major conclusions are summarized in Section 4.

2. Experiments

As shown in Figure 1, a 1/15 scaled model tunnel was constructed based on Froude similarity laws whose accuracy of simulating buoyancy driven flow issues has been widely validated (Ingason, 2008; Ji et al., 2012b). Correlation of the scaling rules is listed in Equation (1) as:

$$\frac{Q_m}{Q_f} = \left(\frac{l_m}{l_f}\right)^{5/2} \tag{1-a}$$

$$T_m = T_f \tag{1-b}$$

$$\frac{V_m}{V_f} = \left(\frac{l_m}{l_f}\right)^{1/2} \tag{1-c}$$

$$\frac{t_m}{t_f} = \left(\frac{l_m}{l_f}\right)^{1/2} \tag{1-d}$$

where Q represents heat release rate, l, T, V, and t, denote length, temperature, velocity, and time, respectively. The model tunnel was 5.0 m long, 0.32 m wide and 0.48 m high. Ceiling and floor of the model tunnel were constructed by the welded steel plates and the sidewalls were made of fireproof glasses. To be noted, even though the model test bed is only 5.0 m long, it is still effective to investigate the fire and smoke spread owing to the following reasons: 1) the tunnel designed with one closed end is usually short in length due to its special function need. For example, the tunnel-style depot being constructed in Chongqing, China, is less than 160 m as it is used for metro train's parking and inspecting only. Besides, the common service tunnel designed with one closed end in the recent report from Gao et al. (2021) is only 60 m long. The current test bed is indeed 75 m in full-scale length, which is even larger than the tunnel reported in Gao et al., (2021). 2) according to the research of Ishikawa et al., (2020), tunnel length has very little influence on the combustion characteristics and longitudinal temperature distribution in a tunnel with one closed end. Besides, tunnel models conducted in some published literature are even more shorter, e.g., 6.0 m at 1/6 scale in Ji et al. (2012a), 6.0 m at 1/10 scale in Xu et al. (2019), 3.0 m (without specific scale ratio) in Zhou et al. (2020), etc. It should be noticed that the aforementioned studies covered a wide range of research topics including both of the burning behavior of pool fire and thermal spread of smoke flow. Hence, we believe measurements obtained from the current test bed are acceptable. The closed end was made of 8 mm thick calcium silicate board and was designed referring to the archetype of tunnel-style depot reported in our previous research (Han et al., 2020; Wang et al., 2021). Besides, a non-combustible ventilation duct (centerline located at X = 1.5 m) in cylinder shape with three dimensions, i.e., $D_{ex} = 100$ mm, 150 mm, and 200 mm, was installed at tunnel ceiling to realize the smoke emission. The ventilation duct was connected to a centrifugal fan equipped with a frequency controller so that an adjustable smoke extraction rate can be produced.

Ethanol, which has a specific heat of combustion 29.64 kJ/kg·K, was utilized as the fuel source as it produces very little soot and harmful gases. It was loaded in five different pool pans to generate different heat release rates. The initial quantity of ethanol for each fuel pan was 75 ml, 125 ml, 175 ml, 250 ml, and 300 ml, with measuring error being less than ± 5 ml. This was to ensure the duration of each test could cover the different stages from initial development, steady burning to the final decay. The initial quantity for each pool fire was prescribed based on the pre-tests before the experiments summarized in Table 1. An electronic balance with accuracy of 0.01 g and measuring range between 0~6200 g was used to document the mass loss rate (MLR) of each individual pool fire and to provide the heat release rate. As shown in Figure 2, fluctuation of the measured MLR and temperature within 400 s~600 s is relatively small. This period was hence assumed as quasi-steady state where measurements were averaged for analysis. In Figure 3, additionally, the measured MLRs from quasi-steady state of pool fires in the case of ceiling extraction system with $D_{ex} = 150$ mm and $D_{ex} = 200$ mm are plotted. Fluctuation of MLRs in all the tests was found to be lower than 0.05 g/s, indicating that smoke extraction effect on MLR is limited regardless of the variation of outlet shape and smoke extraction rate. This seems to be contradictory with some previous literature (Apte et al., 2006; Hu et al., 2011) suggesting that burning rate either increases or decreases as ventilation velocity increases. As matter of the fact, even though extensive studies have been conducted to explore burning rate of pool fires in the regard of windy conditions including both free burn and tunnel environment, no agreement has been achieved on how burning rate varies due to ventilation effect. Several investigators (Welker and Sliepcevich, 1966; Lemaire and Kenyon, 2006; Sjöström et al., 2015) suggested that the burning rate could be considered as independent of the ventilation speed. The present results suggested that the heat feedback to the pool from the rim walls was the dominated factor rather than ventilation effect. Since the heat feedback obtained from rim walls was relatively similar in these tests and the exhaust outlet was not placed right above the fire, it is likely that the extraction system had relatively little influence. Hence, ventilation effect on MLR was neglected and the mean values of MLR were utilized to calculate the heat release rate.

Within the model tunnel, a total number of fifty K-type thermocouples (0.5 mm thickness) divided in three sets namely TR1, TR2, and TR3 were mounted to measure the temperature data. Temperature probes in TR1 were placed 0.02 m underneath the ceiling and divided into two sections. Probes distributed within the closed end and exhaust outlet were installed at the interval of 0.1 m while probes located within the exhaust outlet and tunnel opening were mounted at the interval of 0.2 m. TR2 and TR3 are thermocouple trees individually holding nine probes to detect the vertical temperature distribution. Temperature probes in TR2 and TR3 were installed from Z=0.05 m to Z= 0.45 m with spacing of 0.05 m. The measured temperature data was also documented by a data logging system and was transferred to the laptop every 10 s.

A summary of the main parameters in the experimental tests is given in Table 1. In addition, all the tests were repeated twice under very similar environmental temperatures around 12 ± 3 °C. According to Chen et al. (2011), such temperature fluctuation can be assumed having very limited influence on the measurements. It was therefore neglected in this study. Uncertain analysis is further given in Appendix.

3. Results and discussion

3.1 Temperature distribution

3.1.1 The maximum temperature

The maximum temperature is an important parameter to estimate how much damage is caused by the fire. In the last few decades, plenty of studies were dedicated to investigating the maximum temperature rise in a tunnel fire under different fire scenarios. For the fire burning under quiescent condition, Li et al. (2011b) proposed the following formula:

$$\Delta T_{max} = 17.5\frac{Q^{2/3}}{H_{ef}^{5/3}} \quad (2)$$

where ΔT_{max} is the maximum temperature rise, Q is heat release rate, and H_{ef} is the effective tunnel height. For underground space with one closed end that is similar to the structure explored herein, Ji et al. (2011) found that the maximum temperature was strongly influenced by the fire-end wall distance d and could be generated as:

$$\Delta T_{max} = \left(0.299e^{-0.793d/H_{ef}} + 1\right)16.9\frac{Q^{2/3}}{{H_{ef}}^{5/3}} \tag{3}$$

Very recently, by conducting a set of simulations, Gao et al. (2021) concluded that the maximum temperature in a utility tunnel with one closed end could be calculated based on two sub-regions using Equation (4-a) and Equation (4-b):

$$\frac{\Delta T_{max}}{T_a} = 5.48Q_H^{*2/3}\ ,({}^{d}/_{H_{ef}} > 1) \tag{4-a}$$

$$\frac{\Delta T_{d,max}}{\Delta T_{max}} = 1.82Q_d^{*0.17}\ ,({}^{d}/_{H_{ef}} \le 1) \tag{4-b}$$

where $Q_H^* = \frac{Q}{\rho_a C_p T_a \sqrt{g} {H_{ef}}^{5/2}}$, $Q_d^* = \frac{Q}{\rho_a C_p T_a \sqrt{g} H_{ef} d^{2/3}}$, ρ_a is air density, C_p is specific heat of air, T_a is ambient temperature, and g is gravity.

Figure 4 summarizes the maximum temperature obtained from natural ventilation condition, i.e., $V_{ex} = 0$ m/s and further compares the current measurements with the aforementioned prediction models, i.e., Equation (2)-(4), scaled-model test data from Li et al. (2011b), and full-scale data from Memorial Test (Ingason et al., 2015a) and Liu et al. (2017). Detailed information about the dimension of tunnels in the aforementioned literature are given in Table 2. As shown in Figure 4-(a), experimental measurements are found to be well captured by Equation (2)-(4) in general. Especially, agreement with the model proposed by Ji et al. (2011) is particularly good. Hence, Equation (3) is directly used to estimate the maximum temperature in a naturally ventilated tunnel with one closed end. It can also be observed that the maximum temperatures under a certain heat release rate are almost overlapped, implying that they are insignificantly affected by the dimension of ventilation outlet under natural ventilation. Moreover, when further compare the present measurements with experimental data from multiple scaled tunnels, no obvious difference has been found in Figure 4-(b) even though huge differences exist in tunnel dimension and scale. The overall good agreement exhibited in Figure 4 indicates very convincible results being produced by the current test bed.

Figure 5 plots ceiling temperature profiles under different smoke extraction rates where variation of the maximum temperatures is very small, denoting that smoke extraction has little influence on the maximum temperature. It is also noticed that temperature variation upstream of the fire can be roughly divided into two sections by the smoke outlet. In Region Ⅰ where close to the fire source (from the fire source to the outlet), the influence of smoke extraction rate on ceiling temperature is limited. The reason behind is that ceiling temperature within Region Ⅰ being largely determined by the fire load which is insignificantly influenced by the extraction effect (as illustrated in Figure 3). On the contrary, ceiling temperature in Region Ⅱ (from the outlet to the opening) decreases considerably with the increase of smoke extraction rate as smoke is closer to the exhaust outlet instead of the fire. Meanwhile, the induced air velocity from tunnel opening increases with the increase of smoke extraction rate, resulting in the enhancement of smoke-air entrainment at the interface and the decrease of temperature.

Table 3 summarizes the maximum temperature data from experiments. The maximum temperature differences caused by the smoke extraction are all less than 30 °C, being independent of the variation of outlet shape and extraction rate. This further proves that smoke extraction rate has indistinct influence on the maximum temperature in the fire scenarios explored herein.

3.1.2 Temperature attenuation

Ceiling temperature distribution along the longitudinal centerline is a key parameter for optimizing the evacuation routes in tunnel fire incidents. Numerous studies have been proposed in this regard (Hu et al., 2005; Ingason and Li, 2010) with all predicting an exponential decay of temperature along the ceiling by using the dimensionless temperature ratio. For an underground corridor with one closed end, Hu et al. (2005) established the following simple formula to predict ceiling temperature decay through theoretical analysis and full-scale burning tests:

$$\frac{\Delta T_x}{\Delta T_{x_0}} = exp^{-\varphi x} \tag{5}$$

where x denotes the upstream distance between measuring point and reference point x_0, ΔT_x and ΔT_{x_0} are temperature rises at x and x_0, φ is the temperature attenuation coefficient expressed as $\varphi = \frac{\sigma}{\rho h_s V_s}$, σ is heat transfer coefficient, V_s denotes smoke velocity. By conducting numerous reduced scale tests with various heat release rates and ventilation velocities, Ingason and Li (2010) demonstrated that ceiling temperature in tunnels with low ventilation velocity could be generated as:

$$\frac{\Delta T_x}{\Delta T_{x_0}} = 0.57exp^{-0.13\frac{x}{H_t}} + 0.43exp^{-0.021\frac{x}{H_t}} \tag{6}$$

where H_t represents tunnel height. As for the tunnels utilizing ceiling extraction system, Tang et al.

(2018a) suggested that the temperature attenuation coefficient φ is strongly affected by smoke extraction rate. Two modified temperature attenuation coefficients φ_{up} and φ_{down} were then proposed to account for the influence of extraction effect as:

$$\varphi_{up} = \left(\frac{V_c}{V_c - V_{ex}}\right)^{0.3} \cdot \frac{\sigma D_g}{C_p(0.071Q^{*1/3}H_{ef}^{5/3} - \rho V_{ex} A_{out})} \quad (7\text{-a})$$

$$\varphi_{down} = \left(\frac{V_c}{V_c - V_{ex}}\right)^{0.3} \cdot \frac{\sigma D_g}{C_p(0.071Q^{*1/3}H_{ef}^{5/3})} \quad (7\text{-b})$$

where V_c is the critical velocity, V_{ex} represents smoke extraction rate, D_g is part of the perimeter of the gas flow section that contacts the tunnel surface, and A_{out} is area of outlet.

In this paper, temperature attenuation in Region Ⅰ and Ⅱ will be separately studied because they display totally different responses to smoke extraction rate as shown in Figure 5. In Region Ⅰ, measuring point holding the maximum temperature ΔT_{max} is selected as the reference point, i.e., $\Delta T_{x_0} = \Delta T_{max}$. In Region Ⅱ, measuring point located at X=1.7 m is chosen as the reference point. Thereafter, dimensionless temperature ratio beneath the ceiling is defined as:

$$\frac{\Delta T_x}{\Delta T_0} = \frac{T_x - T_a}{T_0 - T_a} = exp\ (\varphi_{ex} \cdot \frac{x}{H_t}) \quad (8)$$

where φ_{ex} is temperature attenuation coefficient considering the smoke extraction effect, i.e., $\varphi_{ex} \propto f(V_{ex}, A_{out})$. To characterize the different responses of ceiling temperature to the extraction effect, $\varphi_{ex,1}$ and $\varphi_{ex,2}$ are introduced to respectively denote temperature attenuation coefficient in Region Ⅰ and Ⅱ.

It is, however, practically difficult to individually account for the influence of V_{ex} and A_{out} in the meantime as these two variables are strongly influenced by each other. In the light of previous investigation (Chen et al., 2013; Tang et al., 2018a), an 'idealized' induced air velocity V_{in} expressed in Equation (9) is introduced by simultaneously considering the outlet shape and extraction rate to characterize the ventilation effect of ceiling extraction system:

$$V_{in} = \frac{V_{ex} \cdot A_{out}}{A_t} \quad (9)$$

where A_t denotes the area of tunnel cross-section. Meanwhile, to ensure further conclusions made from the present measurements at reduced scale tunnel still being effective in full-scale scenarios, a dimensionless induced air velocity $V_{in}^* = \frac{V_{in}}{\sqrt{gH_t}}$ is utilized. To be noted, V_{in} in Equation (9) is regarded as the 'idealized' value only because it assumes the induced airflow to be evenly distributed across the whole cross-section of the tunnel. Therefore, it is only used to quantify how strong the extraction effect is rather than a real value of air velocity. As matter of the fact, even in a longitudinal ventilated tunnel, a uniform airflow passing through the tunnel cross-section is also very hard to achieve due to the wall boundaries and viscosity. In general, velocity of the airflow is approximately zero at the wall surface and approaches its maximal value at the center of tunnel cross-section. In the practical-oriented research, using such approximation to estimate the induced air velocity considering the smoke extraction effect has been proved to be acceptable (Chen et al., 2013; Li et al., 2016). Furthermore, Equation (9) also requires smoke to be discharged via the outlet only and smoke front must be stopped before it propagates to the external environment. In the present work, many tests fail to meet this requirement due to the limited tunnel length or the relatively small extraction rate. A total number of 13 values of induced air speed are obtained. As some values of V_{in} are very close to each other, five values at an approximately 0.1 m/s interval (V_{in}= 0.06 m/s, 0.12 m/s, 0.23 m/s, 0.32 m/s, and 0.41 m/s) are selected for further analysis.

As illustrated in Figure 5, temperature distribution in a tunnel with ceiling extraction system can be divided into two regions by the outlet. Considering the influence of induced airflow, Figure 6 exhibits fitting results of dimensionless temperature ratio in Region Ⅰ. The plotted data denote good correlation and accuracy of fitting curves. Besides, plotted values at any location, as well as coefficient $\varphi_{ex,1}$ in each sub-graph, are very close to each other, implying that temperature decays in Region Ⅰ are insignificantly affected by either induced air velocity or heat release rate. This is consistent with Equation (5) and (6) proposed by Hu et al. (2005) and Ingason and Li (2010). Thus, averaged values of $\varphi_{ex,1}$ are obtained by Equation (8). Correspondingly, ceiling temperature distribution in Region Ⅰ can be calculated as:

$$\frac{\Delta T_x}{\Delta T_{max}} = exp\,(-0.37 \cdot \frac{x-x_0}{H_t}) \quad (10)$$

Figure 7 displays temperature decays in Region Ⅱ. Plotted values imply that ceiling temperature upstream of the exhaust outlet significantly decreases with the increase of induced air velocity. Such temperature reduction caused by the smoke extraction system seems to be more obvious as heat release rate increases. For example, the average temperature reduction from the reference point to the opened portal is less than 30 ℃ for 2.77 kW fire, approximately 60 ℃ for 7.25 kW fire, and nearly 100 ℃ for 15.56 kW fire. This is likely because quantity of exhausted smoke via the outlet only increases slightly with the increase of extraction rate, due to plug-holing phenomenon (Ji et al., 2012b; Fan et al., 2013) Usually, plug-holing leads to the circumstance that much more fresh air is directly discharged via the outlet and the efficiency of smoke extraction is therefore reduced. Particularly, plug-holing phenomena is likely to occur if smoke extraction rate is strong while the fire load is small. Therefore, for the small fire like 2.77 kW, the increase of smoke extraction rate poorly behaves in reducing ceiling temperature as little extra heat is unloaded owing to the plug-holing phenomena. Nevertheless, effect of plug-holing weakens with the increase of smoke layer thickness underneath the outlet due to the increasing heat release rate. Correspondingly, smoke is extracted more rapidly to the outside and then temperature decreases more remarkably. Results also show a smoke-free region near tunnel opening when the fire size equals to 2.77 kW, 4.81 kW, and 7.25 kW. In such circumstances, the induced air velocity in Equation (9) can be regarded as realistic as smoke is discharged through the exhaust outlet only.

The dimensionless temperature decay calculated by Equation (8) are plotted in Figure 8 along with values of dimensionless ceiling temperature rise (without the smoke-free region). The plotted data and curves exhibit an exponential decay where dimensionless temperature ratios generally decrease from 1.0 to 0, as indicated in the foregoing reports (Hu et al., 2005; Liu et al., 2016). Figure 9-(a) displays the variation of coefficient $\varphi_{ex,2}$ affected by the dimensionless induced air velocity V_{in}^*. Coefficient $\varphi_{ex,2}$ shows a decreasing tendency as V_{in}^* increases. Meanwhile, values of $\varphi_{ex,2}$ are different when heat release rate changes. According to an exponential fitting, $\varphi_{ex,2}$ is then determined as Equation (11):

$$\varphi_{ex,2} = \alpha \cdot exp\,(\beta \cdot V_{in}^*) \quad (11)$$

Where α and β are fitting coefficients. Further, values of coefficients α and β are then plotted in Figure 9-(b). Plotted values denote that 1) variation of α is less affected by heat release rate and 2) values of β follows an exponential decay as heat release rate increases. By using the average value of α and the exponential fitting shown in Figure 9-(b), coefficient $\varphi_{ex,2}$ in Region II is then determined as Equation (12):

$$\varphi_{ex,2} = -0.106 \cdot ex\,p[118\,exp(-81.8Q^*) \cdot V_{in}^*] \quad (12)$$

Combining Equation (8) and Equation (12), dimensionless temperature decay in Region II is expressed as:

$$\frac{\Delta T_x}{\Delta T_0} = exp\,(\varphi_{ex,2} \cdot \frac{x-x_0}{H_t}) \quad (13)$$

where $\varphi_{ex,2} = -0.106 \cdot ex\,p[118\,exp(-81.8Q^*) \cdot V_{in}^*]$.

In Figure 10, predicted temperatures in Region I and II by Equation (10) and (13) are compared with the measurements. Discrepancy between the calculated and measured values is lower than ±10%. Based on Equation (10) and (13), ceiling temperature upstream of the fire is able to be obtained when the point extraction system is used.

3.2 Smoke back-layering length

Smoke back-layering can also occur in tunnels with ceiling extraction systems. In such scenarios, extent of the smoke layer spread is largely influenced by the strength of smoke extraction. As demonstrated in Figure 5, when smoke outlet is mounted upstream of the fire, smoke back-layering length underneath the ceiling is also divided into two regions. The smoke back-layering length in Region Ⅰ can be assumed as a constant value which is equivalent to the distance between the fire and outlet as the smoke is inevitably extracted out. In the following, analysis is hence focused on the smoke back-layering length in Region Ⅱ.

As shown in Figure 11, the concept of virtual fire source is introduced and the definition of back-layering length in Region Ⅱ is illustrated. Heat release rate of virtual fire source is defined as the fire load remained underneath the outlet under $V_{ex} = 0$ m/s, which can be obtained by converting Equation (2) into:

$$Q_{virtual} = (0.057\Delta T_{ex} \cdot H_{ef}^{5/3})^{3/2} \tag{14}$$

Where ΔT_{ex} denotes the temperature rise at smoke outlet and it can be generated by the combination of Equation (3) and (10) in the former section. Figure 11 provides an example of how the back-layering length is produced. Plotted values imply that when smoke extraction rate increases to 1.50 m/s, smoke front stops moving froward at X=3.3 m due to the induced airflow, leaving the upstream region (X=3.3 m ～ X=5.0 m) free of smoke in the meanwhile.

Many scholars previously investigated smoke back-layering length in longitudinal ventilated tunnels with various formulas proposed to represent the relationships between smoke back-layering length, ventilation velocity, and heat release rate. Some examples are quoted below.

Through theoretical analysis, Thomas (1958) proposed the following simple correlation between back-layering length and longitudinal ventilation velocity:

$$l^* = \frac{l}{H} \propto \frac{gH_tQ}{\rho_a T_s C_p V^3 A} \tag{15}$$

Equation (15) was subsequently found to give reasonable predictions for the fire tests in a 1/30 scale model tunnel carried out by Jean-Vantelon et al. (1991), who also proposed a modified correlation between Richardson number and smoke back-layering length in the form:

$$l^* \propto Ri^{0.3} \tag{16}$$

where Ri is Richardson number generated as $Ri = \frac{gQ}{\rho_a T_a C_p V^3 H_t}$. Similarly, measurements in scaled model tests conducted by Deberteix (2000) led to correlation in the form:

$$l^* = 7.5\ (Ri'^{1/3} - 1) \tag{17}$$

where Ri' represents the modified Richardson number known as $Ri' = \frac{T_s - T_a}{T_a} \cdot \frac{gH_t}{V^2}$. Based on dimensionless analysis and small-scale experiments, Li et al. (2010) proposed the following formula to calculate the back-layering length:

$$l^* = \begin{cases} 18.5 \ln\left(0.81 {Q^*}^{1/3}/V^*\right) & , \quad Q^* \leq 0.15 \\ 18.5 \ln(0.43/V^*) & , \quad Q^* > 0.15 \end{cases} \tag{18-a}$$

with term ${Q^*}^{1/3}/V^*$ equivalent to one-third power of Richardson number, Equation (18-a) can be re-written as:

$$l^* = \begin{cases} 18.5 \ln\left(0.81 Ri^{1/3}\right) & , \quad Q^* \leq 0.15 \\ 18.5 \ln(0.43/V^*) & , \quad Q^* > 0.15 \end{cases} \tag{18-b}$$

Weng et al. (2015) proposed the following new formula for the smoke back-layering length in a metro tunnel through measurements in scaled experiments and simulations:

$$l^* = 7.13 \cdot \ln\left(Q^*/{V^*}^3\right) - 4.36 \tag{19}$$

In a tunnel with ceiling extraction system, the governing parameters to determine smoke back-layering length in Region II are heat release rate of the virtual fire, hydraulic tunnel height, induced air velocity caused by extraction effect, air density, ambient temperature, gravity, and heat capacity of air. Correspondingly, back-layering length in Region II, namely l_{ex}, can be broadly considered as:

$$f\left(l_{ex}, Q_{virtual}, H_{ht}, V_{in}, \rho_a, T_a, g, C_p\right) = 0 \tag{20}$$

where H_{ht} is the hydraulic tunnel height. For the cuboid tunnel in this research, the hydraulic tunnel height is calculated as $H_{ht} = 2\frac{W_t \cdot H_t}{(W_t + H_t)}$. Based on the relevant criteria of similarity rules and dimensional analysis (Barenblatt and Isaakovich, 1996), Equation (20) can be re-written as:

$$f\left(\frac{l_{ex}}{H_t}, \frac{Q_{virtual}}{\rho_a {H_{ht}}^2 {V_{in}}^3}, \frac{C_p T_a}{{V_{in}}^2}, \frac{gH_{ht}}{{V_{in}}^2}\right) = 0 \tag{21}$$

Through simple dimensional analysis, it can be converted into:

$$\frac{l_{ex}}{H_{ht}} = f\left[\frac{Q_{virtual}}{\rho_0 C_p T_a \sqrt{g} {H_{ht}}^{5/2}} \left(\frac{V_{in}}{\sqrt{gH_{ht}}}\right)^{-3}\right] = f\left(\frac{Q^*_{virtual}}{{V^*_{in}}^3}\right) \tag{22}$$

Where $Q^*_{virtual} = \frac{Q_{virtual}}{\rho_0 C_p T_a \sqrt{g} {H_{ht}}^{5/2}}$.

In the current study, back-layering occurred in eight of the tests, i.e., Test No. 21, 22, 29, 55, 56, 61, 62, and 68. Smoke back-layering lengths in these tests are plotted in Figure 12-(a). It can be seen that the back-layering length is affected by both heat release rate and induced air velocity, which is consistent with Equation (22). The back-layering length is found to decrease sharply with the increase of induced air velocity and the decrease of heat release rate. By using $\frac{Q^*_{virtual}}{{V^*_{in}}^3}$ as the horizontal axis, variation of the dimensionless back-layering length $\frac{l_{ex}}{H_{ht}}$ is then plotted in Figure 12-(b). By fitting the relationship between the back-layering length, heat release rate, and induced air velocity, smoke back-layering length exceeding the exhaust outlet in a tunnel with ceiling extraction system can be generated as:

$$ {l_{ex}}^* = \frac{l_{ex}}{H_{ht}} = 0.012 + 5.19 ln\left(\frac{Q^*_{virtual}}{{V^*_{in}}^3}\right) \quad \text{(23-a)}$$

$$ {l_{ex}}^* = \frac{l_{ex}}{H_{ht}} = 0.012 + 15.57 ln\left(Ri^{1/3}\right) \quad \text{(23-b)}$$

where the range of $Q^*_{virtual}$ is determined according to the measurements of heat release rate in this study.

Figure 12-(b) compares measurements with the predicted values by Equation (23) and correlations previously proposed by Li et al. (2010) and Weng et al. (2015) as well as values of the smoke back-layering length in a tunnel with two-point extraction system predicted by Jiang et al. (2018b). The comparison indicates that for a certain fire load and ventilation velocity in a tunnel with specific dimensions, the smoke back-layering length upstream the fire in the present study for a tunnel with one closed end, amount of smoke spreading upstream the fire doubled compared to the previous cases with both portals open. This indicates that in a tunnel with one closed portal, higher smoke extraction rate is required to achieve stronger induced air velocity to effectively inhibit the back-layering length in comparison with tunnels with two openings.

In this research, heat release rates in the tests covered the range from a small passenger car to metro carriage fires. The derived correlations are hence limited to such fire size and may not suitable for fires involving heavy goods vehicles (Ingason and Lönnermark, 2005). In addition, distance between the fire and extraction point is another important parameter that may affect the exhaust efficiency and smoke propagation in ceiling extraction system (Chen et al., 2015). This is not addressed herein but will be included in our future work.

4. Conclusion

A series of fire tests were carried out in a 1/15 scaled model tunnel with one closed end to investigate the effect of ceiling extraction system with a single exhaust outlet. Five different heat release rates and numerous smoke extraction rates were utilized. Measurements were analyzed to gain insight into the influence of extraction effect on burning rate, maximum temperature, ceiling temperature attenuation and smoke back-layering length. Two empirical formulas were proposed to predict temperature distribution beneath the ceiling and one further correlation was established to relate the smoke back-layering length with extraction effect. Key findings are summarized as follows.

1) In the tunnel with one closed end, smoke extraction rate has little influence on fuel burning rate and maximum temperature when the exhaust outlet mounted upstream of the fire. When the ceiling extraction system is activated, ceiling temperature distribution upstream of the fire can be divided into two regions namely Region Ⅰ and Ⅱ. In Region Ⅰ, smoke extraction rate has little impact on the temperature, while ceiling temperature decrease rapidly with the increase of smoke extraction rate in Region Ⅱ. An ‘idealized’ induced air velocity V_{in} is introduced to quantify the influence of extraction effect and two empirical models were then correlated with measurements to predict the ceiling temperature distribution.

2) In the tunnel with one closed portal, higher smoke exhaustion rate is required to achieve stronger induced air velocity to effectively inhibit upstream smoke spread and limit the back-layering length in comparison with tunnels with two openings. By introducing the concept of virtual fire source, smoke back-layering length upstream of the exhaust outlet is found to be affected by the coupling effect of heat release rate $Q_{virtual}$ and induced air velocity V_{in}. Based on the dimensional analysis and current measurements, a modified model is proposed to predict the back-layering length upstream of the exhaust outlet.

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.

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Appendix A. Uncertainty analysis

The uncertainty analysis was carried out on the basis of the root-sum-square (RSS) method proposed by Kline and Mcclintock (1953). When the result R of experiment is assumed to be a function of a set of measuring variables, which can be expressed as

$$R = f(x_1, x_2, \dots x_{n-1}, x_n,) \tag{A-1}$$

Then the overall uncertainty in the result δR can be determined by the combination of uncertainty contributed from each variable, which is generated as

$$\delta R = \left(\sum_{i=1}^{n}\left(\frac{\partial R}{\partial x_i}\delta x_i\right)^2\right)^{1/2} \tag{A-2}$$

Where δx_i is the absolute uncertainty of the measured variable x_i.

If R can be calculated in a pure product form of the measured values (Moffat, 1988)

$$R = {x_1}^a {x_2}^b {x_3}^c \dots {x_M}^m \tag{A-3}$$

Then

$$\frac{\delta R}{R} = \left\{\left\{\left(a\frac{\delta x_1}{x_1}\right)^2 + \left(b\frac{\delta x_2}{x_2}\right)^2 + \cdots + \left(m\frac{\delta x_m}{x_m}\right)^2\right\}^{1/2} \tag{A-4}$$

Thereafter, the uncertainty of measurements in this work could be estimate as follows.

(1) Uncertainty of the burning rate measurement

According to the study of Shafee and Yozgatligil (2018), the fuel burning rate per unit area of a pool fire can be calculated as

$$\dot{m}'' = \frac{\Delta m}{\Delta t \cdot A} \tag{A-5}$$

where Δm is the mass loss, Δt is the time interval, and A is the area of burning surface.

Then the uncertainty of the burning rate measurement can be calculated based on Equation (A-2) as

$$\delta\dot{m}'' = \pm\left[\left(\frac{\partial \dot{m}''}{\partial \Delta m}\delta\Delta m\right)^2 + \left(\frac{\partial \dot{m}''}{\partial \Delta t}\delta\Delta t\right)^2 + \left(\frac{\partial \dot{m}''}{\partial \Delta A}\delta\Delta A\right)^2\right]^{1/2} \quad \text{(A-6)}$$

where $\frac{\partial \dot{m}''}{\partial \Delta m} = \frac{1}{\Delta t \cdot A}$, $\frac{\partial \dot{m}''}{\partial \Delta t} = \frac{-\Delta m}{(\Delta t)^2 \cdot A}$, $\frac{\partial \dot{m}''}{\partial A} = \frac{-\Delta m}{\Delta t \cdot A^2}$.

Based on Equation (A6), the relative uncertainty of measured burning rate, namely $\frac{\delta\dot{m}''}{\dot{m}''}$, can be therefore obtained as

$$\frac{\delta\dot{m}''}{\dot{m}''} = \pm\left[\left(\frac{\partial \dot{m}''}{\partial \Delta m}\frac{\delta\Delta m}{\Delta m}\frac{\Delta m}{\dot{m}''}\right)^2 + \left(\frac{\partial \dot{m}''}{\partial \Delta t}\frac{\delta\Delta t}{\Delta t}\frac{\Delta t}{\dot{m}''}\right)^2 + \left(\frac{\partial \dot{m}''}{\partial A}\frac{\delta A}{A}\frac{A}{\dot{m}''}\right)^2\right]^{1/2} \quad \text{(A-7)}$$

where $\frac{\delta\Delta m}{\Delta m}$, $\frac{\delta\Delta t}{\Delta t}$, and $\frac{\delta A}{A}$ are respectively the relative uncertainties of the measured mass loss, time interval in the steady stage, and pool surface area.

The relative uncertainty of measured fuel mass mainly relies on balance readability, linearity, and repeatability. All the values equal to $\pm$ 0.1 g referring to the technical guide of electronic balance. Further, the uncertainties of measured time interval and fuel pans area are controlled by the load cell resolution of $\pm$ 0.2 s and the ruler resolution of $\pm$ 1 mm. By taking these values into Equation (A-7), the maximum relatively uncertainty of the burning rate is lower than $\pm$5 %

(2) Uncertainty of the temperature measurement

In the current study, temperature values were measured by K-type thermocouples whose uncertainty of temperature reading was $\pm$ 0.1 °C. Meanwhile, $\pm$ 1 °C was considered as the conservative value and the relative uncertainty of temperature is calculated as $\frac{\delta T}{T} = \pm(\frac{\pm 1\ ℃}{T\ (℃)})$. Since all the burning tests were conducted under a very similar environmental condition with ambient temperature around 12 °C, the maximal relatively uncertainty of temperature measurement is about $\pm$ 8.3 %.

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Table headings

Table 1. Experimental scheme.

Table 2. Summary of the maximum temperature rise (℃)

Figure captions

Figure 1. A schematic view of the 1/15 model tunnel.

Figure 2. Determination of the range for average in measurements (D_{ex}=100 mm, fuel pan 12 cm × 12 cm for example).

Figure 3. MLRs of pool fires under ceiling extraction effect (D_{ex}=150, 200 mm).

Figure 4. The maximum temperature rise under $V_{ex} = 0$ m/s.

Figure 5. Ceiling temperature affected by extraction velocity V_{ex} (HRR=15.56 kW, $D_{ex} = 200$ mm for instance).

Figure 6. Ceiling temperature affected by the induced air velocity V_{in} in Region I.

Figure 7. Ceiling temperature affected by the induced air velocity V_{in} in Region II.

Figure 8. Dimensionless temperature decays versus induced air velocity V_{in}.

Figure 9. Determination of coefficient $\varphi_{ex,2}$ in Region II.

Figure 10. Comparison between experimental data and predicted values.

Figure 11. Virtual fire and back-layering length in Region II.

Figure 12. Smoke back-layering length under ceiling extraction system.