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Experimental study on backlayering length of thermal smoke flow in a longitudinally ventilated tunnel with blockage at upstream of fire source

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ABSTRACT

Experiments were conducted in a model tunnel to investigate backlayering length of thermal smoke flow in a longitudinally ventilated tunnel with vehicular blockage at upstream of the fire source. Two kinds of blockage ratios were considered and the horizontal distance between the fire and the blockage is in the range of 1–5 m. It is found that with no blockage, the experimental data can be well collapsed by Li model (without blockage). With blockage, the backlayering length is found to be lower than that in an empty tunnel. Both Tang model and Li model (with blockage) fail to predict the backlayering length in our present work. The backlayering length decreases or increases with increasing blockage-fire distance at blockage ratio of 0.26 and given heat release rates, however, at blockage ratio of 0.51 and given heat release rate, the backlayering length increases with increasing blockage-fire distance at large ventilation velocity. At certain heat release rate and ventilation velocity, the backlayering length is larger for cases with smaller blockage ratio, and this discrepancy gradually decreases with increasing blockage-fire distance at larger ventilation velocity, and finally longer backlayering length can be obtained for cases with larger blockage ratio. Larger backlayering length could be obtained for cases with higher heat release rates irrespective of the blockage-fire distance at blockage ratio of 0.26 and given ventilation velocities.

1. Introduction

Tunnel fire safety has attracted extensive attention, especially for the occurrence of several catastrophic tunnel fires (Vuilleumier et al., 2002; Leitner, 2002; Hong, 2004; Carvel and Marlair, 2005), such as the Mont-Blanc road tunnel fire, the Funicular tunnel fire and the Daegu subway tunnel fire. In case of a tunnel fire, longitudinal ventilation is usually adopted as a strategy for smoke control in order to provide a safe environment for personnel evacuation (Oka and Atkinson, 1995; Chow et al., 2010, 2015; Du et al., 2015; Kurioka et al., 2003; Tang et al., 2017a, 2017b, 2017c). If the longitudinal ventilation is not large enough, smoke flow backlayering will appear upstream of the fire source. Studies in literatures have focused mainly on two characteristics of smoke flow backlayering, the backlayering length (Thomas, 1958; Hu et al., 2008a; Li et al., 2010; Weng et al., 2015; Tang et al., 2013; Gannouni and Maad, 2015; Ingason and Li, 2010; Alva et al., 2017; Wang et al., 2016a, 2016b; Zhang et al., 2016; Chen et al., 2013, 2015; Tang et al., 2016; Fan and Yang, 2017) and the critical ventilation velocity (Hu et al., 2008a, 2008b; Weng et al., 2015; Tang et al., 2013; Lee and Tsai, 2012; Li et al., 2012; Wu and Barkar, 2000; Yi et al., 2014; Li and Ingason, 2017; Tang et al., 2017d; Du et al., 2018). In this study, we focus on one of its characteristics the backlayering length, which is defined as the horizontal distance between the front of smoke flow upstream and the fire source location.

Thomas (1958) conducted early study on smoke flow backlayering length and proposed the following formula based on the theory of Froude number.

$$L^* = \frac{L}{H} \propto \frac{gH\dot{Q}}{\rho_0 C_p T_f V^3 A} \tag{1}$$

Deberteix et al. (2001) carried out experiments in a Paris model tunnel and proposed the following equation to predict the backlayering length.

$$L^* = 7.5(Ri^{1/3}-1) \tag{2}$$

where Ri is the Richardson number.

Hu et al. (2008a) carried out full-scale experiments and FDS simulations and proposed the following prediction model for backlayering length.

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Nomenclature

A	tunnel cross-sectional area (m^2)
C_k	experimental constant
C_p	specific heat capacity (kJ/kg/K)
D	blockage-fire distance (m)
D^*	dimensionless blockage-fire distance
Fr	Froude number
g	gravitational acceleration (m/s^2)
H	tunnel height (m)
$\bar{H}$	hydraulic tunnel diameter (height) (m)
L	backlayering length (m)
l_F	full scale length (m)
l_M	reduced scale length (m)
L^*	dimensionless backlayering length
$\dot{Q}$	heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate
$\dot{Q}_F$	full scale heat release rate (kW)
$\dot{Q}_M$	reduced scale heat release rate (kW)
Ri	Richardson number
T_f	gas temperature (K)
V	ventilation velocity (m/s)
V_F	full scale ventilation velocity (m/s)
V_M	reduced scale ventilation velocity (m/s)
v^*	dimensionless ventilation velocity
ρ_0	density of ambient air (kg/m^3)
ϕ	blockage ratio
γ	experimental constant
ε	experimental constant

$$L = \ln[K_2 \cdot (C_k H/V^2)]/0.019 \tag{3}$$

where C_k is the empirical constant, and K_2 is expressed as:

$$K_2 = g \cdot \gamma \left(\dot{Q}^{*2/3}/Fr^{1/3}\right)^{\varepsilon} \tag{4}$$

The well-known prediction model for backlayering length is proposed by Li et al. (2010). Based on dimensionless theory and small-scale experiments, they found that when the dimensionless heat release rate is lower than 0.15, the backlayering length is related to the dimensionless heat release rate and the dimensionless ventilation velocity, however, when the dimensionless heat release rate is larger than 0.15, the backlayering length is independent of the dimensionless heat release rate and only related to the dimensionless ventilation velocity as in the following expression.

$$L^* = \begin{cases} 18.5\ln\left(0.81\dot{Q}^{*1/3}/v^*\right), & \dot{Q}^* \leqslant 0.15 \\ 18.5\ln(0.43/v^*), & \dot{Q}^* > 0.15 \end{cases} \tag{5}$$

Through small-scale experiments and CFD simulation, Weng et al. (2015) investigated the backlayering length in tunnels with different sectional geometries, and proposed a model for predicting the backlayering length as follows.

$$L^* = \frac{L}{\bar{H}} = 7.13\ln\left(\dot{Q}^*/v^{*3}\right) - 4.36 \tag{6}$$

Zhao et al. (2018) investigated the backlayering length of fire smoke in tunnels with non-axisymmetric section and traditional symmetrical section, and proposed two new prediction models for the dimensionless backlayering length.

Above studies on backlayering length of smoke flow only consider fire scenarios when there is no vehicle blockage in tunnels. However, in case of a real tunnel fire accident, vehicles usually have to stop and get stuck at the upstream of the fire source. The existence of vehicle blockage will make the ventilation flow inside a tunnel become much more complex than that in an empty tunnel.

Studies on backlayering length of smoke flow by considering the effect of vehicular blockage have also been conducted. Li et al. (2010) carried out small-scale experiments to investigate the effect of vehicle blockage on backlayering length by positioning a model vehicle 40 mm above the tunnel floor. The model vehicle occupied about 20% of the tunnel cross-sectional area, that is, the blockage ratio of the model vehicle is about 0.2. It was found that the backlayering length is decreased compared to fire scenarios without blockage. The backlayering length with blockage inside a tunnel can be expressed as:

$$L^* = \begin{cases} 13.5\ln\left(0.63\dot{Q}^{*1/3}/v^*\right), & \dot{Q}^* \leqslant 0.15 \\ 13.5\ln(0.33/v^*), & \dot{Q}^* > 0.15 \end{cases} \tag{7}$$

Tang et al. (2013) investigated the effect of blockage-fire distance on backlayering length by positioning a vehicular blockage at the upstream of the fire source. A correlation (Eq. (8)) was proposed to predict the backlayering length with factors of both blockage ratio and blockage-fire distance included. From the correlation, it can be observed that when the blockage-fire distance is smaller than a certain value (3.3 times the hydraulic tunnel height), the backlayering length decreases with the increasing blockage-fire distance, however, when the blockage-fire distance is larger than that value, the backlayering length is the same as that in a tunnel without blockage.

$$L^* = \begin{cases} 18.5\ln\{0.81\dot{Q}^{*1/3}/([1-\phi+\phi(0.3D/\bar{H})]v^*)\}, & D/\bar{H} \leqslant 3.3,\ \dot{Q}^* \leqslant 0.15 \\ 18.5\ln(0.81\dot{Q}^{*1/3}/v^*), & D/\bar{H} > 3.3,\ \dot{Q}^* \leqslant 0.15 \\ 18.5\ln\{0.43/([1-\phi+\phi(0.3D/\bar{H})]v^*)\}, & D/\bar{H} \leqslant 3.3,\ \dot{Q}^* > 0.15 \\ 18.5\ln(0.43/v^*), & D/\bar{H} > 3.3,\ \dot{Q}^* > 0.15 \end{cases} \tag{8}$$

Ingason and Li (2010) carried out tests in a model tunnel by adopting wood cribs as fire source, and proposed the following correlation for backlayering length.

$$L^* = 17.3\ln(0.4/v^*) \tag{9}$$

Gannouni and Maad (2015) numerically studied the effect of blockage on backlayering length by placing an obstacle upstream of fire. Blockage ratio of the obstacle is 0.31, and its location relative to

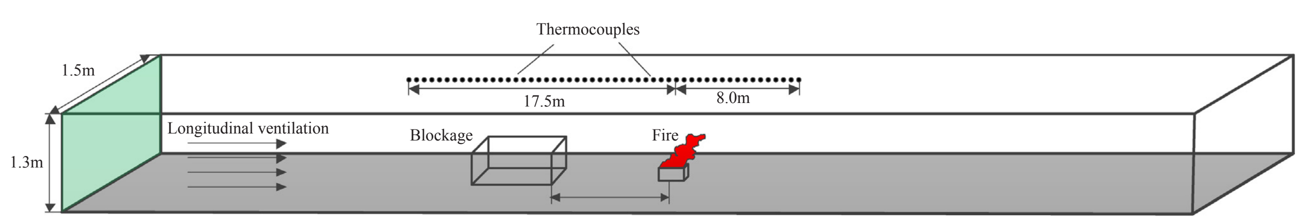

Fig. 1. Schematic of model tunnel and experimental setup.