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Prediction of smoke back-layering length under different longitudinal ventilations in the subway tunnel with metro train

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A B S T R A C T

Due to the small width and the large train blockage ratio in subway tunnel, the smoke back-layering will be different from that in the wider road tunnel with small vehicle blockage ratio. In the train blockage region of tunnel, the velocity of longitudinal ventilated air-flow interacting with the back-flowed smoke gas is different from that in the upstream tunnel without train blockage. Then the back-flowed smoke gas might be prevented in the train blockage region with higher ventilation velocity, otherwise it would be stopped in the upstream tunnel without train blockage but with lower ventilation velocity. They were taken into consideration separately and an equivalent fire source was introduced by dividing the dimensionless heat release rate of fire source into two parts in the cases where the smoke back-layering length is longer than metro train length. A series of full-scale numerical simulations are carried out with FDS to investigate the smoke back-layering length in subway tunnel with different train lengths and longitudinal ventilation velocities. The simulation results indicate that the influence of metro train length on the smoke back-layering is great and cannot be ignored any more. A global correlation model is proposed based on the dimensionless analysis and simulation results.

1. Introduction

As an effective way to relieve the road traffic jam in metropolis, metro systems get fast development in China. Due to the special structure of subway tunnel, long and confined, fire is always a great threaten to the passengers' safety. Notable examples includes the subway fire accident in Baku, Azerbaijan, leading to 558 fatalities and 269 people injured and the Daegu metro fire in South Korea, resulting in 272 casualties and 318 people missing. Most of the death were killed by poisonous smoke gas, according to the accident investigations. Hence, it is of great significance to get smoke gas under control in the subway tunnel fire in terms of safe evacuating and casualties reduction.

Longitudinal ventilation is widely used in the tunnel fire to prevent the smoke gas spreading in the upstream direction. When the ventilation velocity is lower than critical value because of the ventilation failure, there will be smoke back-layering, which has been investigated by many researchers.

By analyzing the Froude number, Thomas (1958) firstly suggested that the buoyancy and inertial force should be equal at the critical condition, he has firstly proposed an equation to predict the back-layering length as following:

$$l^* = \frac{L}{H} \propto \frac{gHQ}{\rho_0 c_p T_f V^3 A} \tag{1}$$

Hu et al. (2008) believed when the static pressure difference between the smoke gas front and the ambient is equal to the hydraulic pressure of incoming fresh air, the back-layering front stops propagating under the tunnel ceiling. Based on this theory, they deduced an equation to predict the back-layering length in road tunnel.

$$L = \ln\left[g \cdot \gamma \left(\frac{Q^{*2/3}}{Fr^{1/3}}\right)^{\varepsilon} \cdot \frac{C_k H}{V^2}\right] \Big/ 0.019 \tag{2}$$

Combining the dimensionless analysis and small-scale experiments together, Li et al. (2010) have derived that when the dimensionless heat release rate is lower than 0.15, the dimensionless back-layering length varies as one-third power of the dimensionless heat release rate. While it is only dependent on the longitudinal ventilation velocity at higher heat release rates. The relationship is described as following:

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Nomenclature

H	tunnel height (m)
ϕ	blockage ratio
L_T	metro train length (m)
L	back-layering length (m)
Q	total heat release rate (kW)
A	tunnel cross-sectional area (m^2)
Q^*	dimensionless heat release rate
V	longitudinal ventilation velocity (m/s)
$\overline{H}$	hydraulic diameter of tunnel (m)
$\dot{m}$	mass flux in the tunnel (kg/s)
C_k	a constant in Eq. (2)
ρ_0	ambient density (kg/m^3)
T_f	flame temperature (K)
c_p	thermal capacity of air (J/(kg K))
g	gravitational acceleration (m/s^2)
A_b	cross-sectional area of blockage (m^2)
l^*	dimensionless smoke back-layering length
L_{f-b}	distance between fire source and blockage (m)
l_B^*	smoke back-layering length in the block region
γ and ε	constants in Eq. (2)
l_U^*	smoke back-layering length in the upstream region without train
L_{ST}	smoke back-layering length in the train blockage region in the case (ii) (m)
Q_U^*	dimensionless heat release rate of equivalent fire source at the rear of train
Q_T^*	dimensionless heat release rate of equivalent fire source at the front of train

$$l^* = \begin{cases} 18.5\ln(0.81Q^{*1/3}/V^*), & Q^* \leqslant 0.15 \\ 18.5\ln(0.43/V^*), & Q^* > 0.15 \end{cases} \quad (3)$$

Because the fires are usually caused by the vehicle crash or other traffic accidents in the tunnel, many researchers have focused on the blockage effect of vehicles on the smoke back-layering under longitudinal ventilations.

Li et al. (2010) has also investigated the influence of a model vehicle occupying 20% of tunnel cross-sectional area on the back-layering length in their small-scale experiment. It has been revealed that the blockage has a significant effect where the back-layering length is much decreased relative to those without blockage.

With different relative positions between fire source and blockage, the tunnel fire behavior with vehicular blockage has been studied by Lee and Tsai (2012). They found that the back-layering length is larger with fire source put directly at the downstream of blockage compared to the situations where no blockage in the tunnel.

Using a longitudinal ventilated model tunnel, Tang et al. (2013) studied the effect of vehicular blockage on the smoke back-layering length. The results showed that with the increase in fire-blockage distance, the back-layering length firstly decreases, and then approaches to constants similar to those without blockage. A dimensionless modification coefficient is introduced to account for this effect. Finally, a global model is proposed to predict back-layering length including factors of both blockage ratio and fire-blockage distance.

$$L^*_{blockage(L)} = \begin{cases} 18.5\ln\left\{0.81Q^{*1/3}\Big/\left(\left[\frac{A-A_b}{A}+\frac{A_b}{A}(0.3L_{f-b}/\overline{H})V^*\right]\right)\right\}, L_{f-b}/\overline{H} \leqslant 3.3,\ Q^{*1/3} \leqslant 0.15 \\ 18.5\ln(0.81Q^{*1/3}/V^*),\ L_{f-b}/\overline{H} > 3.3,\ Q^{*1/3} \leqslant 0.15 \\ 18.5\ln\left\{0.43\Big/\left(\left[\frac{A-A_b}{A}+\frac{A_b}{A}(0.3L_{f-b}/\overline{H})V^*\right]\right)\right\}, L_{f-b}/\overline{H} \leqslant 3.3,\ Q^{*1/3} > 0.15 \\ 18.5\ln(0.43/V^*),\ L_{f-b}/\overline{H} > 3.3,\ Q^{*1/3} > 0.15 \end{cases} \quad (4)$$

From more literature reviews (Huo et al., 2015; Lai et al., 2014; Lin et al., 2014; Wang et al., 2015; Yi et al., 2014), it can be concluded that most of the previous studies on tunnel fire focused on the road tunnels, which has different aspect ratio compared with subway tunnel. According to the results of Ryou and Lee's experiments, the aspect ratio affects the growth and development of smoke in tunnel fires (Lee and Ryou, 2005). When the fire occurs in a narrow tunnel, the air entrainment of smoke plume will be restrained by the sidewalls and the heat feedback from the heated boundaries also will increase, resulting in the different critical ventilation velocities and smoke back-layering length in the tunnel with same hydraulic diameter but different aspect ratios (Ji et al., 2012). Besides, the blockage ratio in subway tunnel is usually above 0.5, which is obviously larger than that in road tunnel with lower 0.3. Therefore, the smoke back-layering length in the narrower subway tunnel will be different from that in the wider road tunnel for the same heat release rate of fire.

Besides, the influence of vehicle length on the smoke movement is usually ignored in the previous studies, because there was only one vehicle taken into consideration and even for the HGV (Heave Goods Vehicle), its length is usually about 18 m, shorter than 20 m. Therefore, the velocity of ventilated air-flow interacting with smoke gas was not strengthened in the upstream tunnel except that in the vehicle blockage region (but this region is relatively small), which might results in larger difference or deviation between experimental results and theoretical derivations under the condition of long vehicle blockage. Furthermore, the metro train length is about 120 m in common, which is much longer than that of vehicle in road tunnel, the length effect on the smoke propagation should not be ignored any more. Most importantly, the influence of metro train length on the smoke back-layering has never been revealed in the former tunnel fire studies.

Therefore, in this study, we focus on the influence of metro train length on the smoke back-layering in the subway tunnel fire. Through numerical simulations, the smoke back-layering lengths are investigated under different longitudinal ventilations in the tunnel with metro trains of different lengths. Then, a new prediction model of smoke back-layering length is proposed based on the analysis and simulation results.

2. Assumption and dimensionless model analysis

Through experiments, Wu and Bakar (2000) has clearly demonstrated that for a tunnel having the same height, the critical velocity varied with tunnel width. The tunnel height cannot sufficiently reflect the impact of tunnel geometric characteristics on smoke flow. In fact, the dynamic flow of air inside the tunnel is more a function of tunnel hydraulic diameter including the effect of tunnel width, rather than depending solely on the tunnel height (Ris, 1970). So the present work uses the tunnel hydraulic diameter, $\overline{H}$, to replace the tunnel height, H, as the characteristic length in the dimensionless analysis. The tunnel hydraulic diameter, $\overline{H}$, is defined as the ratio of 4 times the cross-sectional area to the tunnel wetted perimeter. Here are the dimensionless-normalized smoke back-layering length, heat release rate and longitudinal ventilation velocity: