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A numerical study on smoke movement in a metro tunnel with a non-axisymmetric cross-section

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ABSTRACT

In this paper, a numerical study was carried out to analyze the effect of non-axisymmetric (semi-arched) cross-section on the smoke movement in metro tunnel fires by using FDS 6. Two models including Tunnel one (a tunnel with a non-axisymmetric cross-section) and Tunnel two (a traditional tunnel with a symmetrical section) were built. The back-layering length, critical ventilation velocity and temperature distribution were compared and analyzed. Two new prediction models for the dimensionless back-layering length and the critical ventilation velocity in semi-arched metro tunnel fires were proposed, and they were compared with the available data in previous studies and the prediction models proposed by other researchers. For the temperature distribution in Tunnel one, the maximum gas temperature beneath the ceiling appears at the center line of ceiling above the fire, and it is slightly higher than that in Tunnel two under the same fire HRR and the same ventilation velocity because of the less fresh air entrainment. In addition, the likely reasons for the different smoke movement between two tunnels were subsequently explained in this paper.

1. Introduction

The internal space of the metro tunnel is relatively closed, and once a fire occurs, the high temperature and toxic smoke will not only damage the overall stability of the tunnel structure, but also cause vast casualties. In the 21st century, there have been some famous tunnel fire accidents including Kaprun tunnel fire (2000) in Austria, Gotthard Tunnel fire (2001) in Switzerland, Daegu metro fire (2003) in South Korea, Viamala tunnel fire (2006) in Switzerland, and Burnley tunnel fire (2007) in Austria, etc. (Han and Lee, 2009; Meyer, 2003; Weng et al., 2014). Smoke movement in tunnels is a very complicated process, therefore, how to control the smoke movement effectively, and exhaust the flue gas safely in tunnel fires become a major problem that must be addressed in the design of ventilation and smoke exhaust in metro tunnels (Liu et al., 2016; Weng et al., 2015, 2014).

In the previous studies (Chow et al., 2015; Hu et al., 2013a, 2007b, 2008b; Hua et al., 2011; Lee and Ryou, 2006; Lee and Tsai, 2012; Wu and Bakar, 2000), transverse ventilation (or semi-transverse ventilation) and longitudinal ventilation have been identified as the two prevalent ventilation models. Although transverse ventilation (or semi-transverse ventilation) has been used in the tunnel smoke control, longitudinal ventilation is still the mainstream tunnel ventilation strategy due to its relatively lower investment. Under the longitudinal ventilation, the back-layering phenomenon (back-layering length), critical velocity (the minimum air velocity to prevent smoke from spreading against the longitudinal ventilation flow) and the longitudinal temperature distribution of fire-induced ceiling flow have become the research focus for the researchers from all over the world.

1.1. Back-layering length

The back-layering length of the smoke is the length of the flue gas along the upstream direction, when the longitudinal ventilation velocity of the tunnel is less than the critical longitudinal ventilation velocity (see Fig. 1). For the study of back-layering length, based on Thomas's earlier works (Thomas, 1968), a back-layering length model was reported (Beard and Carvel, 2005):

$$\frac{L}{H_d} = C_d \cdot \frac{gQ}{\rho_a T_a c_p V^3 H_d} \quad (1)$$

where L is the back-layering length, H_d is the height from the surface of the fire source to the ceiling in the tunnel, the proportionality constant

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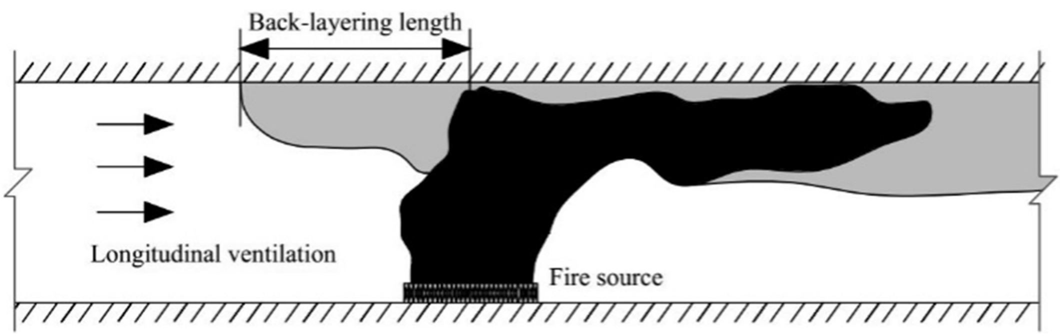

Fig. 1. The back-layering length in tunnel fire under the longitudinal ventilation.

C_d should be determined from experiments, Q is the heat release rate (HRR) of fire source (kW), ρ_a is air density (kg/m^3), c_p is the air specific heat capacity at constant pressure (J/(kg K)), g is the acceleration of gravity (m/s^2), T_a is the ambient temperature (K), V is the longitudinal ventilation velocity (m/s).

Deberteix et al. (2001) carried out small-scale experiments to test the back-layering length of the gas in a Paris Metro model tunnel with a height of 0.163 m. The relationship between the dimensionless back-layering length and the Richardson number was proposed:

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

$$\text{with } Ri = \frac{gQ}{\rho_a T_a c_p V^3 H} \tag{2b}$$

where L^* is the dimensionless back-layering length and defined as $L^* = L/H$, H is the height of the tunnel, Ri is the Richardson number.

Based on theoretical analysis, full-scale experiments and FDS simulations, Hu et al. proposed the back-layering length model (Hu et al., 2008a):

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

$$\text{with } K_2 = g \cdot \gamma (Q^{*2/3}/Fr^{1/3})^{\varepsilon} \tag{3b}$$

$$\text{and} \begin{cases} \gamma = 1.77, \varepsilon = 6/5 & (Q^{*2/3}/Fr^{1/3} < 1.35) \\ \gamma = 2.54, \varepsilon = 0 & (Q^{*2/3}/Fr^{1/3} > 1.35) \end{cases} \tag{3c}$$

where C_k is a dimensionless constant by which the thickness of the smoke layer is related to the tunnel height. Q^* is the dimensionless heat release rate of the fire and defined as $Q^* = Q/\rho_a c_p T_a g^{1/2} H_d^{5/2}$, F_r is the Froude number and defined as $F_r = V^2/gH_d$.

The well-known prediction formula of back-layering length was based on the dimensionless HRR Q^* and dimensionless velocity V^*. The model proposed by Li et al. and Weng et al. could be expressed as:

$$L^* = f(Q^{*1/3}, V^*) \tag{4}$$

The prediction model proposed by Li et al. (2010):

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

where $Q^* = Q/\rho_a c_p T_a g^{1/2} \mathrm{H}^{5/2}$, $V^* = V/\sqrt{g\mathrm{H}}$.

The model proposed by Weng et al. (2016):

$$L^* = \begin{cases} 6.41\ln\left(\frac{Q^*}{V^{*3}}\right) - 3.58 & \zeta \geqslant 1 \\ 8.32\ln\left(\frac{Q^*}{V^{*3}}\right) - 5.81 & \zeta < 1 \end{cases} \tag{6}$$

where $Q^* = Q/\rho_a c_p T_a g^{1/2} \overline{H}^{5/2}$, $V^* = V/\sqrt{g\overline{H}}$. $\overline{H}$ is the hydraulic tunnel height, defined as the ratio of four times the cross-sectional area to the tunnel wetted perimeter (m). ζ is the sectional coefficient and defined as $\zeta = A/H^2$, A is the area of the tunnel cross section (m^2).

1.2. Critical ventilation velocity

The critical ventilation velocity is the minimum air velocity to prevent smoke from spreading against the longitudinal ventilation flow. This means that when the back-layering length is equal to 0, the corresponding longitudinal ventilation velocity is exactly equal to the critical velocity. To predict the critical ventilation velocity, several models have been established by Thomas (1968), Heselden (1976), Oka and Atkinson (1995), Hu et al. (2008a), Wu and Bakar (2000), Li et al. (2010) and Weng et al. (2016). According to the Fr number theory, Thomas proposed the prediction model formula (Thomas, 1968):

$$V_c = k\left[\frac{gQ_c}{\rho_a C_p T_f}\right]^{1/3} \tag{7}$$

where V_c is the critical ventilation velocity (m/s), Q_c is the convective heat release rate (HRR) of fire source (kW), T_f is the smoke temperature (K), k is a constant obtained by experimental testes.

Heselden adopted a similar theoretical analysis method to derive a new prediction formula (Heselden, 1976):

$$V_c = CK\left[\frac{gQT_f}{c_p \rho_a T_a^2 W}\right]^{1/3} \tag{8}$$

where C, K is constant obtained by experimental tests, W is the width of the tunnel (m).

Based on the theoretical analysis, Hu et al. proposed the critical ventilation model by conducting some full-scale experiments and FDS simulations (Hu et al., 2008a):

$$V_c = [C_k g H \cdot \gamma \cdot Q^{*2\varepsilon/3} (g \cdot H_d)^{\varepsilon/3}]^{1/(2+2\varepsilon)} \tag{9}$$

The models proposed by Oka and Atkinson (1995), Wu and Bakar (2000), Li et al. (2010) and Weng et al. (2016) are the dimensionless prediction formulas. Based on the dimensional analysis, Oka and Atkinson introduced the dimensionless HRR Q^* and dimensionless velocity V^*, and proposed the prediction critical velocity model (Oka and Atkinson, 1995):

$$V_c^* = \begin{cases} k_v \left(\frac{Q^*}{0.12}\right)^{1/3} & Q^* < 0.12 \\ k_v & Q^* \geqslant 0.12 \end{cases} \tag{10}$$

where $Q^* = Q/\rho_a c_p T_a g^{1/2} H^{5/2}$, $V^* = V/\sqrt{g\mathrm{H}}$, k_v is a constant which could be chosen as 0.22, at most as 0.38. The above formula is only applicable to the calculation of the critical longitudinal ventilation velocity in the tunnel with the same height and different widths. This model is restricted by the geometry of the tunnel.

The model proposed by Wu and Bakar (2000):

$$V_c^* = \begin{cases} 0.40\left(\frac{Q^*}{0.20}\right)^{1/3} & Q^* \leqslant 0.20 \\ 0.40 & Q^* > 0.20 \end{cases} \tag{11}$$

where $Q^* = Q/\rho_a c_p T_a g^{1/2} \overline{H}^{5/2}$, $V^* = V/\sqrt{g\overline{H}}$.