Tunnelling and Underground Space Technology 79 (2018) 134–142

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Effects of ambient pressure on smoke back-layering in subway tunnel fires

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ARTICLE INFO

Keywords:
Ambient pressure
Back-layering length
Subway tunnel fire

ABSTRACT

This paper investigates the effects of ambient pressure on smoke back-layering in subway tunnel fires with and without train blockage. A series of numerical simulations were conducted in a 1/4 small-scale tunnel with different heat release rates (40–160 kW), longitudinal ventilation velocities (0.2–0.8 m/s) and ambient pressures (60–100 kPa). The smoke back-layering lengths under different conditions are analyzed, and the results show that under the same heat release rate and ventilation velocity, the back-layering length increases with decreasing ambient pressure due to the weak inertial force of longitudinal airflow led by the low air density. The Li's and Zhang's models, which can well predict the smoke back-layering length under regular pressure, are modified for the reduced pressure. The constant increment of back-layering length between adjacent ambient pressures, which mainly depends on the heat release rate, is used to correct Li's model. The smoke back-layering length under the low ambient pressure can be predicted by this modified model without train blockage. With train blockage considered, new models are developed by introducing both equivalent and virtual fire sources for predicting the smoke back-layering length under the low ambient pressure, which is shown to well reproduce the simulation results.

1. Introduction

Tunnel fires, as one of the most catastrophic disasters in tunnels, have attracted extensive concerns in recent decades (Ji et al., 2012; Fan et al., 2013; Tang et al., 2013). The toxic smoke induced by fires, which spreads a long distance along the tunnel driven by the buoyancy, is the most fatal factor that might lead to huge property loss and casualties (Chen et al., 2013; Gao et al., 2015, 2016; Tang et al., 2016; Yang et al., 2017). Hence, understanding the smoke behaviors is highly important and the critical ventilation and back-layering length have been of the major concerns for many years (Guo et al., 2012; Guo and Zhang (2014); Zhang et al., 2012; Weng et al., 2014, 2015; Chen et al., 2015; Yao et al., 2016; Tang et al., 2017; Meng et al., 2018).

Recently, the number of high altitude tunnels in China is sharply increasing, such as the Guangjiao Tunnel at an altitude of 3700 m, the Balang Mountain Tunnel at an altitude of 3800 m and the Changla Mountain Tunnel at an altitude of 4500 m (Tang et al., 2014; Yan et al., 2017; Ji et al., 2017). Apart from these road tunnels, many subway tunnels have been built in the plateau regions and cities. For example, the Lanzhou metro system has been built at an altitude of 1517 m where the ambient pressure is 84 kPa, and the Kunming metro system has been built at an altitude of 1891 m where the ambient pressure is 80 kPa. The Xining and Lhasa metros will be built at altitudes of 2261 and 3658 m with ambient pressures as low as respective 77 and 65 kPa. The high-altitude environment is characterized by reduced ambient pressure, low air density and low air temperature (Yan et al., 2017). Thus, the fire behaviors in high-altitude tunnels should be quite different from those at normal altitude (Yan et al., 2017), which is worthwhile studying.

With regard to normal altitude and regular pressure, Li et al. (2010) conducted reduced-scale experiments to investigate the critical velocity and the back-layering length in tunnel fires. Based on experimental data, a correlation was proposed to predict the back-layering length:

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

where

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_0 c_p T_0 g^{1/2} H^{5/2}} \tag{2}$$

$$V^* = V/\sqrt{gH} \tag{3}$$

Tang et al. (2013) conducted experiments in a longitudinal ventilated tunnel to study the effects of a vehicular blockage at the upstream of the fire source on the back-layering length and the critical velocity. A global model was proposed to predict the back-layering length including the factors of cross-sectional blockage ratio and blockage-fire

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https://doi.org/10.1016/j.tust.2018.05.011
Received 3 February 2018; Received in revised form 24 April 2018; Accepted 10 May 2018

Nomenclature

A	cross-sectional area of the tunnel [m^2]
A_b	cross-sectional area of the blockage [m^2]
c_p	air thermal capacity [J/(kg·K)]
D^*	characteristic fire diameter
Fr^*	modified Froude number
g	gravitational acceleration [m/s^2]
H	tunnel height [m]
$\overline{H}$	hydraulic diameter of the tunnel [m]
K_t	temperature decay coefficient
L	smoke back-layering length [m]
L^*	dimensionless smoke back-layering length
L_b	blockage-fire distance [m]
L_t	metro train length [m]
L_v	smoke back-layering length induced by the virtual fire source [m]
P	ambient pressure [kPa]
$\dot{Q}$	heat release rate [kW]
$\dot{Q}^*$	dimensionless heat release rate
$\dot{Q}_e$	heat release rate of the equivalent fire source [kW]
$\dot{Q}_{L=L_t}$	critical heat release rate of the fire source [kW]
$\dot{Q}_v$	heat release rate of the virtual fire source [kW]
R	ideal gas constant [J/(mol K)]
T_0	ambient temperature [K]
V	ventilation velocity [m/s]
V^*	dimensionless ventilation velocity

Greek

ΔL	constant increment of smoke back-layering length between adjacent ambient pressures [m]
ΔT_{max}	maximum temperature rise above the fire source [K]
ΔT_v	maximum temperature rise above the virtual fire source [K]
δx	nominal size of a mesh cell
ρ_0	air density [kg/m^3]
φ	blockage ratio

distance:

$$L^* = \begin{cases} 18.5\ln\left\{0.81\dot{Q}^{*1/3}/\left(\left[\frac{A-A_b}{A}+\frac{A_b}{A}(0.3L_b/\bar{H})\right]V^*\right)\right\}, \\ 18.5ln(0.81\dot{Q}^{*1/3}/V^*), \\ 18.5\ln\left\{0.43/\left(\left[\frac{A-A_b}{A}+\frac{A_b}{A}(0.3L_b/\bar{H})\right]V^*\right)\right\}, \\ 18.5ln(0.43/V^*), \end{cases}$$

$$\begin{array}{l} \frac{L_b}{\bar{H}} \leqslant 3.3,\ \dot{Q}^* \leqslant 0.15 \\ \frac{L_b}{\bar{H}} > 3.3,\ \dot{Q}^* \leqslant 0.15 \\ \frac{L_b}{\bar{H}} \leqslant 3.3,\ \dot{Q}^* > 0.15 \\ \frac{L_b}{\bar{H}} > 3.3,\ \dot{Q}^* > 0.15 \end{array} \tag{4}$$

Zhang et al. (2016a, 2016b) investigated the influence of metro train blockage on the smoke back-layering in subway tunnel fires. A new correlation involving the metro train length was developed for the back-layering length:

$$L^* = \begin{cases} 6.956ln\left(\frac{1.712\dot{Q}^{*1/3}}{V^*/(1-\varphi)}\right),\ \dot{Q}^{*1/3} \leqslant \dot{Q}^{*1/3}_{L=L_t} \\ L_t^* + 19.342ln\left(\frac{0.935\dot{Q}_v^{*1/3}}{V^*}\right),\ \dot{Q}^{*1/3} > \dot{Q}^{*1/3}_{L=L_t} \end{cases} \tag{5}$$

These former studies have brought us a new perspective on the smoke back-layering under different circumstances. However, they have just covered normal altitude and regular ambient pressure. Once the ambient pressure is reduced, the air density and air entrainment rate will decrease, which may have impacts on the smoke back-layering in tunnel fires (Tang et al., 2014; Yan et al., 2017). Tang et al. (2014) numerically studied the longitudinal distributions of temperature and CO concentration in tunnel fires under two ambient pressures (100 and 64 kPa) and indicated that the longitudinal decay profile of CO concentration is independent of the pressure while the temperature decays faster at the lower pressure. Wang et al. (2015, 2017a, 2017b) conducted a set of fire experiments and simulations to investigate the smoke behaviors in an aircraft cargo compartment with varying pressures, revealing that the ceiling smoke temperature decays faster and the CO spreads faster under reduced pressures. Yan et al. (2017) conducted full-scale fire experiments in a road tunnel at a high altitude of 4100 m. The experimental results showed that the mass loss rate (MLR) at the high altitude is lower than the theoretical prediction with regular pressure and the temperature at the low altitude decays faster with increasing altitude. Ji et al. (2017, 2018), conducted numerical simulations to explore the effects of ambient pressure on smoke mass transport and temperature distribution in tunnel fires. Mathematical models of average smoke mass flow rate and longitudinal smoke temperature distribution in the one-dimensional spread stage were derived using dimensional analysis.

So far, little research has been conducted on the smoke back-layering under the reduced ambient pressure in high-altitude tunnel fires. Moreover, if the blockage effect of vehicle on the back-layering is also taken into account, the issue becomes more complicated. Therefore, in the current study, we firstly investigate the influence of low pressure on the smoke back-layering in a subway tunnel without train blockage. The conventional model for the back-laying length is modified to improve its applicability under the reduced pressure. Furthermore, with train blockage considered, new models are also proposed for the back-layering length under the reduced pressure based on theoretical analysis and simulation results. This research may benefit the engineering applications of fire detection, smoke control and safe evacuation in high-altitude tunnels.

2. Numerical modelling

Fire Dynamics Simulator (FDS) of version 6.5.3 is employed to perform the numerical modeling. FDS is an open source CFD code and is developed based on the Navier-Stokes equations appropriate to low Mach number applications (Gannouni and Maad, 2015). The code has been widely used in fire research field and its validity has been extensively verified (Zhang et al., 2016b; Ji et al., 2017, 2018).

In this study, large eddy simulation (LES) is used to model the turbulence (Gao et al., 2012). The LES uses the Deardorff turbulent viscosity and the subgrid scale (SGS) kinetic energy is taken from an algebraic relationship based on the scale similarity. A single step, mixing-controlled chemical reaction model which uses three lumped species is used for combustion. The lumped species are air, fuel, and products. The radiative heat transfer is included in the current simulations via resolving the radiation transport equation (RTE) for the gray gas with 100 discrete angles. The RTE is solved using a finite volume method (FVM) similar to the one for convective transport. The reason of choosing the latest version of FDS instead of the previous versions to perform the fire modeling is because when calculating the baroclinic torque term in the momentum equation, the assumption used in previous versions is satisfactory for most geometries but could fail with the long, sealed tunnels. This has frequently led to the numerical instability in tunnel fire simulations with the previous versions and the problem is