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Experimental studies on fire-induced temperature distribution below ceiling in a longitudinal ventilated metro tunnel

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ABSTRACT

A series of experiments were carried out in a small-scale model tunnel with dimensions of 13 m(Length)∗0.32 m(Width)∗0.48 m(Height) to investigate the fire-induced temperature distribution below ceiling in a longitudinal ventilated metro tunnel. The different temperature distributions with varying longitudinal ventilation velocity and fire size at both upstream and downstream side have been compared and analyzed. The relative smoke flow directions to the longitudinal ventilation flow in the upstream and downstream are different, obvious “convection shear phenomenon” occurred only in the upstream side. And it was shown that smoke temperature distribution in the upstream back layer seemed to be much more sensitive to the ventilation velocity than that in the downstream flow. Based on the experimental data, a modified coefficient $1/\gamma$ which was related to the ventilation velocity and fire size was introduced into the upstream temperature decay equation. A new modified temperature decay model for the temperature decay at upstream side of fire source was proposed. Moreover, the comparison of the modified coefficient value indicated that Tang's model underestimated the rate of temperature decay in the upstream side of fire source, the modified coefficient in his study was apparently smaller.

1. Introduction

Along with urban development and enlargement, the fire safety in metro tunnel has attached much attention from both the academia and society. In the metro rail system, any potential dangers may cause people to be at risk due to its special long-narrow structure and the high concentration of passengers. The previous statistics showed that smoke was the most fatal factor in tunnel fires (Babrauskas et al., 1998). The good design and operation of tunnel ventilation systems could effectively control the smoke in tunnel fires. Longitudinal and transverse (or semi-transverse) ventilation have been identified as the two most prevalent ventilation strategies (Du et al., 2016). Compared with longitudinal ventilation, transverse ventilation has some certain advantages, such as the better effect on the smoke control. But, for the metro rail system, longitudinal ventilation is still the main tunnel ventilation strategy worldwide due to its relatively lower investment (Weng et al., 2014, 2015). In order to well understand the fire growth in tunnels, to guide the design of the installation locations of fire detectors and selection of heat sensors, and to organize the fire evacuation effectively, the fire-induced temperature distribution below ceiling in longitudinal ventilated metro tunnels should be well investigated (Fan et al., 2013; Ji et al., 2016).

Many studied have been carried out to study the temperature distribution along tunnels in the recent decades (Hu et al., 2005; Hu et al., 2007, 2013, 2014; Lönnermark and Ingason, 2005; Li et al., 2011, 2012b; Liu et al., 2016; Tang et al., 2014). The study of temperature distribution along tunnels mainly includes the research content of the two aspects: the maximum smoke temperature and longitudinal temperature decay. For the maximum smoke temperature, many empirical equations were proposed by fire research scholars. The models from Kurioka et al. and Li et al. became the typical ones among them (Kurioka et al., 2003; Li et al., 2011).

The model proposed by Kurioka et al. is as follows (Kurioka et al., 2003):

$$\frac{\Delta T_{max}}{T_a} = \gamma'(Q^{*2/3}/Fr^{1/3})^{\varepsilon'} \tag{1a}$$

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

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Nomenclature

Q	heat release rate of the fire (kW)
Q^*	dimensionless heat release rate of the fire
Q_c	convective heat release rate of the fire (kW)
Fr	Froude number
ΔT_{max}	maximum smoke temperature rise at downstream region (K)
T_a	ambient temperature (K)
c_p	air specific heat capacity at constant pressure (kJ/*kg* K)
g	acceleration of gravity (m/s^2)
u	longitudinal ventilation velocity (m/s)
u^*	dimensionless ventilation velocity
u_c	critical ventilation velocity (m/s)
u_c^*	dimensionless critical ventilation velocity
r	fire source radius (m)
H	tunnel height (m)
W	tunnel width (m)
H_{ef}	vertical distance between fire source bottom and tunnel ceiling (m)
H_d	height from surface of fire source to the tunnel ceiling (m)
$\overline{H}$	hydraulic diameter of the tunnel (m)
ΔT	smoke temperature rise at a distance of x from the reference point (K)
ΔT_0	smoke temperature rise at the reference point (K)
T_0	smoke temperature of the reference point (K)
T_x	smoke temperature at a distance of x from the reference point (K)
St	Stanton number
h'	total heat transfer coefficient (W/m^2 K)
h_c	convective heat transfer coefficient (W/m^2 K)
h_r	radiative heat transfer coefficient (W/m^2 K)
$\dot m$	smoke mass flow rate (kg/s)
m'	absorbed mass flow rate by ceiling extraction (kg/s)
x_{max}	position that has the maximum flow temperature (m)
D	perimeter of the smoke section that contacts the tunnel surface (m)
w_e	entrainment velocity (m/s)
S	cross section area of smoke layer (m^2)
$\dot q$	heat loss rate from the smoke layer to the boundaries (kW)
T_s	smoke temperature (K)
T_{sur}	temperature of boundary surface (K)

Greek letters

ρ_a	air density (kg/m^3)
γ' and ε'	coefficient in Eqs. (1a) and (1b)
ξ	sectional coefficient
ε	emissivity
σ	Boltzmann constant
β	entrainment coefficient

$$Q^* = Q/\rho_a c_p T_a g^{1/2} H_d^{5/2} \tag{1c}$$

$$F_r = u^2/gH_d \tag{1d}$$

The model proposed by Li et al. (2011):

$$\Delta T_{max} = \begin{cases} Q/ur^{1/3}H_{ef}^{5/3} & (u' > 0.19) \\ 17.5Q^{2/3}/H_{ef}^{5/3} & (u' \leqslant 0.19) \end{cases} \tag{2a}$$

$$\text{with } u' = u/u'' \tag{2b}$$

$$u'' = (Q_c g/r\rho_a c_p T_a)^{1/3} \tag{2c}$$

In addition, Kurioka et al. (2003) conducted extensive scaled experiments and proposed an empirical equation for predicting the position that has the maximum flow temperature under the tunnel ceiling. Hu et al. (2013) conducted a set of experiments to study the influence of slop on the maximum ceiling gas temperature. Liu et al. (2016) introduced the sectional coefficient ξ to divide tunnels into two categories ($\zeta \geqslant 1$ and $\zeta < 1$) and studied the influence of the cross section on the maximum smoke temperature under the tunnel ceiling. Li and Ingason (2012) carried out experiment to study the maximum ceiling gas temperature in a large tunnel fire, they pointed out that the maximum gas temperature is found to be 1350 °*C* in large tunnel fires.

For the gas temperature decay along the tunnel beneath the ceiling, Delichatsios (1981) studied the spread of smoke under a beamed ceiling and proposed the longitudinal temperature distribution model of tunnel fire smoke:

$$\frac{\Delta T}{\Delta T_{max}}\left(\frac{W}{2H}\right)^{1/3} = 0.49\exp\left\{-6.67St\frac{x}{H}\left(\frac{W}{2H}\right)^{1/3}\right\} \tag{3}$$

The temperature decay along the tunnel ceiling or corridor appears to follow exponential decay laws. Evers built the analogous empirical equation (Evers, 1978):

$$\frac{\Delta T}{\Delta T_0} = \frac{T_x - T_a}{T_0 - T_a} = K_1\exp(-K_2 x) \tag{4a}$$

$$\text{with } K_2 = \frac{K_1 h' W}{\dot m c_p} \tag{4b}$$

where K_1 is an empirical constant.

The above equation was verified by Kim et al. in the fire research in a 11.83 m long corridor (Kim et al., 1998). However, Bailey et al. conducted a numerical simulation in an 8.51 m long corridor by using LES model and proposed a power law distribution (Bailey et al., 2002):

$$\Delta T = \Delta T_0\left(\frac{1}{2}\right)^{x/16.7} \tag{5}$$

In recent years, Hu's model (Hu et al., 2004a, 2004b, 2005) became the most widely used empirical equation. He proposed the exponential decay law of the temperature with the assumption of no entrainment of air from the counter flow:

$$\frac{\Delta T}{\Delta T_0} = \frac{T_x - T_a}{T_0 - T_a} = e^{-k(x - x_0)} \tag{6a}$$

$$\text{with } \quad k = \frac{h'D}{\dot m c_p} \tag{6b}$$

However, most of the above equations, such as Eq. (6a), could only apply to the one-dimensional spreading phase after the maximum temperature point in downstream of the fire source (Tang et al., 2016). The temperature distribution at the upstream side of fire source, on which only a few reports have been reported up to now (Hu et al., 2008; Zhang et al., 2016a, 2016b), and no regular conclusion has been obtained. Among them, Hu et al. (2008) used an exponential function to fit the experimental data and got the smoke temperature distribution upstream along the tunnel, which could be expressed as:

$$\frac{\Delta T}{\Delta T_{max}} = e^{-0.019x} \tag{7}$$

Hu et al. (2007, 2008) and Zhang et al. (2016a, 2016b) conducted a series of experiments and pointed out that the dimensionless temperature rise in the upstream along the tunnel ceiling falls into an exponential decay and the decay coefficient k_{up} was mainly related to the longitudinal ventilation. The dimensionless temperature decay given by