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Estimation of smoke arrival time in tunnel fires

Liming Li [a,*], Xudong Cheng [b], Yu Cui [c], Wenhui Dong [a], Zhibin Mei [a]

[a] Shenyang Fire Research Institute, Shenyang, Liaoning 110034, PR China
[b] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230027, PR China
[c] School of Resources and Environment Engineering, Shandong University of Technology, Zibo, Shandong 255049, PR China

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ABSTRACT

The estimation of smoke arrival time in tunnel fires is helpful to comprehensive fire risk assessment and effective fire evacuation, while few studies focused on this topic. A model to estimate the arrival time of fire smoke in tunnels is derived based on the smoke temperature distribution along the tunnel ceiling. The predictions from the model are compared to experimental data from one past study, which shows good agreements. The influencing factors of the smoke arrival time are studied based on the model. Results show that the Stanton number is the main influencing factor. The smoke arrival time increases with the increase of the Stanton number.

1. Introduction

Tunnel or long corridor fires have gained much concern recently in the field of fire safety science since several fatal tunnel fires occurred (Brousse et al., 2001; Hong, 2004; Kirkland, 2002; Rail Accident Investigation Branch, 2010). Smoke control is one of the most concerned topics as fire smoke spread along the tunnels will threaten the lives inside and the tunnel structure, which may cause disasters such as injuries, loss of lives, severe property damage, service disruption, or even loss of public confidence in tunnels as a safe means of transportation (Kang, 2010).

In a tunnel or long corridor fire, the spread process of the smoke flow under the tunnel ceiling could be described in three steps (Delichatsios, 1981; Kunsch, 2002; Li et al., 2012c) as shown in Fig. 1:

1. The formation of the axisymmetric radial fire plume, i.e., from (a) to (b).
2. The occurrence of a density jump. In this step, the fire plume first contacts the tunnel ceiling and turns to ceiling jet (this transition part is called turning region, i.e., from (b) to (c)) and then it intercepts the tunnel sidewalls (from (c) to (d)), and a transition from radial to one-dimensional flow occurs. The density jump occurs during this process, either before or after the fire plume intercepts the sidewalls depending on the tunnel height-to-width ratio.
3. The formation of the one-dimensional flow. After the density jump, a one dimensional flow along the tunnel is generated, which moves toward the tunnel exits under the ceiling.

The main hazards come from the spread of the one-dimensional smoke flow due to its toxicity and high temperature. Thus, some studies focused on the smoke control, especially the critical velocity of the longitudinal ventilation (Chow et al., 2010; Hu et al., 2008; Ko et al., 2010; Li et al., 2012a, 2010), while some others focused on the most representative fire parameter – temperature, i.e., the maximum temperature (Hu et al., 2006; Kurioka et al., 2003; Li et al., 2011, 2012b; Li and Ingason, 2012) and the temperature decay (Chen, 2008; Hu et al., 2007b; Li et al., 2012c, 2012d). These are helpful studies to tunnel fire safety design. However, few studies have been reported to investigate the arrival time of the fire smoke. Knowledge of smoke arrival time in tunnel fires could help to estimate the fire risk and to assist appropriate fire evacuation.

Based on the authors' previous work on smoke temperature distribution under natural ventilation, a model for smoke arrival time will be derived in this paper. The predictive ability of the model will be justified using a set of experimental data. The main influencing factors will also be discussed.

2. Model derivation

The authors' previous study presented a model for the temperature distribution of the one-dimensional fire smoke flow along tunnel ceiling under natural ventilation (Li et al., 2012c). This mod-

* Corresponding author. Tel.: +86 2431535651.
E-mail addresses: liliming@mail.ustc.edu.cn, liliming@syfri.cn (L. Li).

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Nomenclature

C_p	smoke specific heat, kJ kg^{-1} K
f	friction coefficient, –
g	gravitational acceleration, m/s^2
h	thickness of the smoke flow, m
h_{conv}	heat transfer coefficient, W m^{-2} K
H	tunnel height, m
H_{ef}	height from the bottom of fire source to tunnel ceiling, m
Pr	Prandtl number, –
Q	fire heat release rate, kW
St	Stanton number
t	time, s
T	temperature, K
u	flow velocity along tunnel, m/s
W	tunnel width, m
x	variable for the distance starting from the fire source, m

Greek symbols

ϕ	aspect ratio of the tunnel cross–section, $\phi = H/W$
ρ	smoke density, kg m^{-3}
ΔT	$T - T_a$, K
τ	characteristic time, s

subscript

0	value at the position where the one-dimensional flow starts
a	ambient value

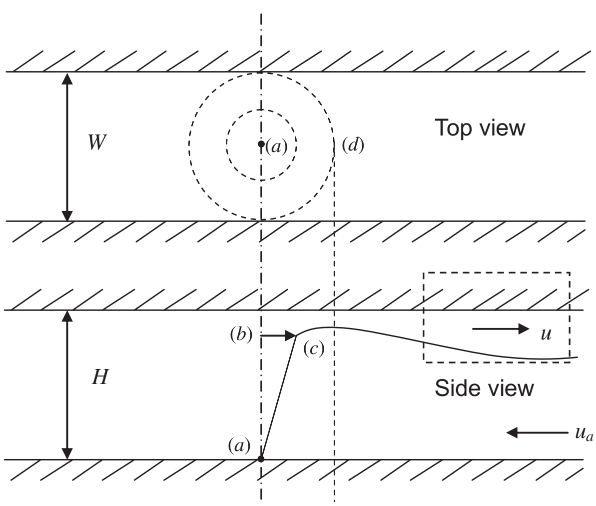

Fig. 1. The development of fire smoke in tunnels.

el comes to the following form if the start point of the one-dimensional smoke flow is taken as the reference position:

$$\frac{\Delta T}{\Delta T_0} = \exp\left\{-St\frac{(2\phi + 20.3\phi^{-1})(x - W/2)}{H}\right\} \tag{1}$$

When the density difference between the smoke flow current and the ambient airflow is small, Bailey et al. (2002) proposed

$$u = 0.7\sqrt{gh\frac{\Delta T}{T_a}} \tag{2}$$

This correlation applies to the start point of the one-dimensional smoke flow as:

$$u_0 = 0.7\sqrt{gh\frac{\Delta T_0}{T_a}} \tag{3}$$

Taking Eqs. (2) and (3) into Eq. (1) reveals

$$\frac{u}{u_0} = \sqrt{\frac{\Delta T}{\Delta T_0}} = \exp\left\{-\frac{St}{2}\frac{(2\phi + 20.3\phi^{-1})(x - W/2)}{H}\right\} \tag{4}$$

Eq. (4) shows the decay of the smoke velocity along tunnel ceiling. The following dimensionless variables are defined taking the tunnel height H and u_0 as the characteristic quantities:

$$\hat{x} = \frac{x - W/2}{H}, \quad \hat{u} = \frac{u}{u_0}, \quad \hat{t} = \frac{t - t_0}{\tau}, \quad \tau = \frac{H}{u_0} \tag{5}$$

where the hat ^ indicates the dimensionless variables. Taking these variables into the definition of velocity, $\hat{u} = d\hat{x}/d\hat{t}$, the following expression will be obtained after integration:

$$\begin{aligned} &\hat{t} = \tfrac{1}{k}(e^{k\hat{x}} - 1) \\ &k = St(2\phi + 20.3\phi^{-1})/2 \end{aligned} \tag{6}$$

The above equation shows the estimated time for the moving fire smoke to arrive at a certain position. This model will be examined later.

To get the dimensional time from Eq. (6), the following two quantities should be given, the excess temperature, ΔT_0, and the flow thickness, h. For small fires (i.e., flames do not impinge on tunnel ceiling) and natural ventilation condition, ΔT_0 could be approximately estimated from Li et al.'s correlation for maximum smoke temperature (Li et al., 2011)

$$\Delta T_0 = 17.5\frac{Q^{2/3}}{H_{ef}^{5/3}} \tag{7}$$

For smoke flow thickness, h, it could be estimated from the correlation by Kunsch (2002) with the assumption that the thickness of the fire-induced flow keeps constant at h_0 (Li et al., 2012c, 2012d), which is

$$h_0 = 0.02\left(\frac{\pi}{2}\right)^2\left(\frac{H}{W}\right)H \tag{8}$$

Taking all these variables into Eq. (6) gives:

$$t = \frac{1.54\sqrt{H^{2/3}T_a/\left(g\phi Q^{2/3}\right)}}{St(2\phi + 20.3\phi^{-1})/2H}\left[\exp\left\{\frac{St(2\phi + 20.3\phi^{-1})(x - W/2)}{2H}\right\} - 1\right] \tag{9}$$

From Eq. (9) it is seen that the main factors that could influence the smoke arrival time are the Stanton number, St, and the fire heat release rate, Q. This will be discussed later.

3. Experimental data

The experimental data used here are from Hu et al. (2007a). The experiments were carried out in a tunnel with the scale of 88 m × 8 m × 2.65 m, as shown in Fig. 2. Two diesel pool fires were used near the north end, which had the heat release rate of 0.8 MW and 1.5 MW, respectively. No mechanical ventilation systems were used. The south end was open providing natural ventilation while the north end was closed. 10 pairs of infrared beams and 49 points