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Theoretical and experimental study on longitudinal smoke temperature distribution in tunnel fires

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ABSTRACT

In order to study the hazard of the hot smoke which is toxic and in high temperature, a new heat balance equation is established to study the heat and mass transfer during smoke propagation process. The heat balance equation can be converted into an inhomogeneous linear differential equation of first order in the end, where the thermal radiation, air entrainment and heat convection are considered. The solution to this differential equation is proposed and the parameters are discussed. Furthermore, the factors that influence the smoke temperature distribution are discussed according to the equation we established. Additionally, in order to examine the solution of smoke temperature distribution in longitudinal direction, a set of small scale experiments are carried out where the variables are the ventilation velocity and heat release rate. Otherwise, a comparison with other tests' data both from small scale and real tunnels is conducted. Results show that the smoke temperature distribution correlates in good agreement with the solution we assumed both in our experiments and other tests, confirming that the theoretical analysis and the application of this formula in determining the smoke temperature distribution in tunnel fires in longitudinal direction and assessing the hazard the hot smoke. The investigation presented here considers only the cases when the ratio of the length to the width of the tunnel is large so that the smoke movement can be considered as One-dimensional Horizontal Spread.

1. Introduction

Recently, with the rapid development of economy, especially in the field of infrastructure where the investment is increasing, more and more urban tunnels and railway tunnels have been constructed. At the same time, however, the frequency of tunnel fires is also increasing, causing great casualties and property losses. As we all know, heat, smoke and poisoned gases are the killers which cause unexpectable death [1]. Thus, the maximum smoke temperature beneath the tunnel ceiling to which the tunnel structure is exposed needs to be estimated to help detect the fire and its location in early stage. However, the maximum smoke temperature beneath the tunnel ceiling varies with heat release rate, longitudinal ventilation velocity and tunnel geometry structures. Such knowledge is important to somebody who needs to understand and estimate the development of tunnel fires and the maximum smoke temperature beneath the tunnel ceiling [2].

An empirical equation to estimate the maximum smoke temperature was proposed by Kurioka et al. [3]. Kurioka et al. conducted a series of experiments to investigate the relationship between the maximum temperature and heat release rate (HRR), getting a general formula:

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

where

$$\frac{Q^{*2/3}}{\mathrm{Fr}^{1/3}} < 1.35, \gamma = 1.77, \varepsilon = 1.2$$

$$\frac{Q^{*2/3}}{\mathrm{Fr}^{1/3}} > 1.35, \gamma = 2.54, \varepsilon = 0$$

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Nomenclature

ΔT_{ma}	maximum excess gas temperature beneath the ceiling [°C]
T_a	ambient temperature [°C]
T	the temperature of hot smoke [°C]
x	the distant from the fire source [m]
Q_r	the heat released by hot smoke [W]
Q_{conv}	the convection heat between smoke and the ceiling [W]
Q_e	the heat that cold air absorbs [W]
Q_{rad}	the heat that hot smoke radiate [W]
c_s	the specific heat capacity of hot smoke [J/(kg·°C)]
c_a	the specific heat capacity of air [J/(kg·°C)]
$\dot{m}_s$	the mass rate of smoke [kg/s]
$\dot{m}_a$	the mass rate of air entrained by smoke [kg/s]
ρ_a	the density of air [kg/m³]
ρ_s	the density of smoke [kg/m³]
u_s	the velocity of smoke [m/s]
h_o	the height of smoke layer [m]
w	the width of the tunnel [m]
Δu	the relative velocity between smoke and air [m/s]
h_k	coefficient of convective heat transfer [W/m²·K]
h_r	coefficient of radiative heat transfer [W/m²·K]
β	coefficient of air entrainment [-]
α	variable combined with multiple variables [m⁻¹]
$\dot{m}$	the mass loss rate [kg/s]
k_f	coefficient of thermal conductivity [W/m·K]

The dimensionless heat release and the Froude Number in Eq. (1) are defined as follows:

$$Q^* = \frac{Q}{\rho_0 c_p T_0 g^{1/2} H_{ef}^{5/2}}, Fr = \frac{V^2}{gH_{ef}} \tag{2}$$

Hu et al. [2] compared Eq. (1) with their full scale experimental data, and it showed good agreement. However, according to Eq. (1), $Fr^{1/3}$, which is dominated by the Froude Number, is the denominator of the equation and it cannot be zero. When ventilation velocity approaches zero, the maximum smoke temperature approaches infinity large. Thus, when there is no ventilation or the ventilation velocity is very low, which can occur in real tunnel fires, the estimated maximum smoke temperature cannot be predicted correctly. Hence, when there is no ventilation or the ventilation velocity is very low, Eq. (1) is not applicable. What's more, the consequences were obtained from experiments and empirical correlations, no theoretical analysis was performed.

Li et al. gave a theoretical analysis of the maximum smoke temperature beneath the tunnel ceiling based on plume theories and proposed their own equation [4]. Furthermore, they summarized the previous researchers' experiments' data and further developed their own equation [5]:

$$\Delta T_{\max} = \begin{cases} \dfrac{Q}{V b_{f0}^{1/3} H_{ef}^{5/3}}, V' > 0.19 \\ 17.5\dfrac{Q^{2/3}}{H_{ef}^{5/3}}, V' \le 0.19 \end{cases} \tag{3}$$

where V is the ventilation velocity and b_{f0} is radius of the fire source.

The dimensionless ventilation velocity in Eq. (3) is defined as follow:

$$V' = V \Bigg/ \left(\frac{gQ}{b_{fo}\rho_o c_p T_0}\right)^{1/3} \tag{4}$$

Their consequence showed that the maximum smoke temperature could be divided into two regions, which is the same as Kurioka et al.'s [3]. Moreover, as for the region with low ventilation velocity (ie $V' \le 0.19$), there is no ventilation velocity V in the denominator, meaning that the problem we proposed does not exist.

Otherwise, just knowing the maximum smoke temperature is not enough. We need to know the temperature field in tunnel fires. Hence, it's meaningful to investigate the maximum smoke temperature distribution in tunnel fires and build models theoretically. Based on previous data obtained from full scale [6,7] and small scale [8–10]experiments, as well as from numerical researches [11,12], researchers have found easy-to-use method to determine the temperature distribution.

Evers and Waterhouse builded their own model through experiments [13], the result is as follow:

$$\frac{\Delta T}{\Delta T_0} = K_1 e^{-K_2 x} \tag{5}$$

However, the conclusion is obtained from experimental results without theoretical analysis. Hu, otherwise, studied smoke temperature distribution theoretically and got a formula [14]:

$$\frac{\Delta T}{\Delta T_0} = e^{-K(x-x_0)} \tag{6}$$

which has the same form as [13] and they are all exponential attenuation. However, Hu did not consider the effect of air entrainment and assumed that it was considerably small and could be neglected.

This paper gives a theoretical analysis of the smoke movement and its heat transfer considering the effect of air entrainment, convective heat transfer between hot smoke and the ceiling and heat radiation at the same time to study the main reason of temperature attenuation and temperature distribution. Furthermore, small-scale experiments are conducted to verify the theoretical analysis. The comparison with other tests' data is also performed and results show good agreement.

2. Experiment setup

The experiments were conducted in a small-scale model tunnel as shown in Fig. 1. A scale ratio 1:10 was applied in current cases. The tunnel was 16.5 m long, 1.3 m wide and 0.65 m high. The tunnel's board and roof were made of galvanized sheet and both sidewalls were made of fire proof glasses. Froude law [15] had been applied to build this model tunnel. The relationship between the model tunnels and real tunnels can be calculated using Eqs (7)–(9) according to Froude law:

$$\frac{T_m}{T_p} = 1 \tag{7}$$