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Effect of smoke screen height on smoke flow temperature profile beneath platform ceiling of subway station: An experimental investigation and scaling correlation

Na Meng [a,b], Longhua Hu [a,*], Shi Zhu [a], Lizhong Yang [a]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao, Shandong 266590, China

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ABSTRACT

This paper presents experimental study on the effect of smoke screen height on temperature distribution of fire-induced flow beneath platform ceiling of subway station. A reduced-scale (1:10) subway station experimental model including the lobby, platform and tunnel is developed. The temperature beneath the platform ceiling is measured by K-type thermocouples at different fire heat release rates (HRR) simulated by using a LPG gas burner for different smoke screen heights at the stairs connecting the platform and the lobby. Results show that the temperature profile can be well correlated by an exponential decay function. The temperature decays faster generally as indicated by a higher exponential power index (K), which increases with increase in smoke screen height or decreases with increase in HRR of the fire. Based on scaling analysis, a global formula is proposed $\frac{(W+2H)^{1/5}}{\dot{Q}^{1/15}(Z_0-H)^{1/3}}$, to correlate the value of K proportionally, as well verified by the experiments.

1. Introduction

Many fires happened in subway tunnels and subway stations in recent years and these accidents usually cause severe consequences due to intensive crowds (Zhong, 2007; Ji, 2009; Jiang et al., 2009; Shi et al., 2012). One of the well-known subway fires is the Daegu subway fire in 2003 (Park, 2004; Hong, 2004), which caused about 200 people killed and 150 injured. By now, numerous studies (Chen et al., 2003; Rie et al., 2005; Park et al., 2006; Yuan and You, 2007) on subway fires have been conducted, which are mainly based on numerical simulation method.

The underground subway station is usually composed of two floors, the first underground floor as the lobby floor and the second underground floor as the platform floor. Nowadays, the island platform is the most widely used type in China (Zhong, 2007), as shown in Fig. 1. It is usually 10–14 m wide, and more than 100 m long, typical tunnel-shape building. In case of a platform fire, in order to well evaluate the safety of the passengers, to effectively conduct personnel evacuation and to correctly direct the installation locations of fire detectors, the temperature distribution of fire-induced flow beneath platform ceiling of subway station is needed to be well investigated.

As for the tunnel-shape building, studies have already been conducted to investigate the characteristics of smoke propagation along the ceiling and the corresponding smoke control in this special building (Oka and Atkinson, 1995; Kim et al., 1998; Kunsch, 2002; Wu and Bakar, 2002; Atkinson and Wu, 1996; Hu et al., 2007a, 2008a). The smoke spread process in a tunnel-shape space could be divided into four stages (Kunsch, 1999), as shown in Fig. 2. In the first stage, the fire plume rises up and impinges onto the tunnel ceiling. In the second stage, the fire plume spreads radially and then reaches the tunnel sidewalls. The third stage is the transition from the radial spreading to one-dimensional spreading. Then the fully-developed one-dimensional smoke flow is formed and spreads horizontally under the tunnel ceiling.

The temperature of the fire-induced flow will decrease during its propagation under the tunnel ceiling due to its heat loss to the surroundings. Studies have already been conducted to investigate the temperature reduction during the smoke spreading along the tunnel ceiling. Delichatsios (Delichatsios, 1981) studied the smoke propagation under a beamed ceiling and presented an expression for temperature variation along the beamed ceiling for the fully developed one-dimensional smoke flow.

* Corresponding author. at: State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China. Tel.: +86 551 63606446; fax: +86 551 63601669.
E-mail address: hlh@ustc.edu.cn (L. Hu).

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Nomenclature

A_c	smoke flow section area, m^2
C_p	specific heat at constant temperature, J/(kg·°C)
g	gravitational acceleration, m/s^2
H	height of the smoke screen, m
H_0	ceiling height in Eq. (1), m
h_c	convective heat transfer coefficient, W/(m^2·°C)
K	temperature decay factor
K_1	empirical constant in Eq. (2)
K_2	parameter in Eq. (2), related to heat transfer constant, corridor width and mass flow rate and specific heat at constant pressure
L_c	half width of the corridor in Eq. (1), m
l	characteristic length, m
L	contact length between the flow and the walls, m
$\dot{m}$	mass flow rate of the fire-induced flow, kg/s
$\dot{m}_0$	mass flow rate of the fire-induced flow at reference position, kg/s
Nu	Nusselt number
$\dot{q}$	convective heat loss of the flow, W/m^2
$\dot{Q}$	fire heat release rate, kW
Re	Reynolds number
St	Stanton number
T	temperature of the flow, °C
T_a	temperature of the ambient, °C
ΔT	average temperature rise, °C
ΔT_0	average temperature rise at reference position, °C
u	flow velocity, m/s
W	width of the platform ceiling, m
x	distance from the fire, m
x_0	reference position, m
Z	distance from the platform floor to the bottom of the smoke screen, m
Z_0	height of the platform ceiling, m
w_e	horizontal entrainment coefficient, m/s
ρ	flow density, kg/m^3
ρ_a	ambient air density, kg/m^3
μ	viscosity coefficient of the flow, N·S/m^2
λ	correlation slope

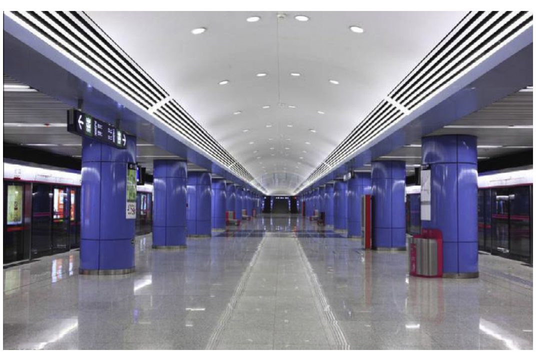

Fig. 1. Photo of the platform floor of a subway station.

$$\frac{\Delta T}{\Delta T_0}\left(\frac{L_c}{H_0}\right)^{1/3} = 0.49\exp\left\{-6.67\mathrm{St}\frac{x}{H_0}\left(\frac{L_c}{H_0}\right)^{1/3}\right\} \tag{1}$$

where ΔT is the average temperature rise at distance x, and ΔT_0 is the average temperature rise at reference position, L_c is the half width of the corridor, H_0 is the ceiling height and St is the Stanton number.

The above expression implies that the temperature variation along the tunnel ceiling follows an exponential correlation. Evers and Waterhouse (He, 1999) conducted studies on the temperature distribution of hot gas under the ceiling when smoke flowed from a fire compartment into a corridor and presented an empirical expression.

$$\frac{\Delta T}{\Delta T_0} = K_1\exp(-K_2 x) \tag{2}$$

where K_1 is an empirical constant, and K_2 is related to heat transfer constant, corridor width and mass flow rate and specific heat at constant pressure. Following studies also demonstrate that the temperature decay in the smoke flow along the tunnel ceiling also follows the exponential function (Hu et al., 2005, 2007b, 2008b; Li et al., 2012).

However, as for the building structure, there is still difference between tunnels or corridors and the platform. The platform is usually connected with the lobby floor through stairs. And what's more, smoke screen, a smoke blocking wall, is usually installed below the platform ceiling, right in front of the stairs, as shown in Fig. 3. That's to say, there is a horizontal opening in the platform ceiling, and right in front of the opening, smoke screen hangs down the platform ceiling. Due to the above differences of architectural structure, there are fundamental differences between smoke

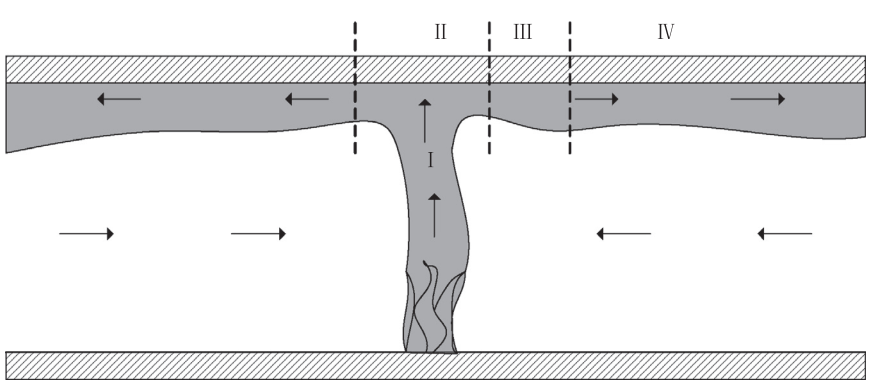

Fig. 2. Schematic drawing of the smoke propagation in a tunnel-shape space.