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Fire-induced temperature distribution beneath ceiling and air entrainment coefficient characteristics in a tunnel with point extraction system

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ABSTRACT

This study investigates the effect of a point extraction system on air entrainment characteristics of a one-dimensional smoke movement stage in a ventilation tunnel under various ceiling extraction velocities. Reduced scale model tunnel experiments are conducted. The vertical smoke layer temperature is recorded, and the variation characteristics of smoke layer thickness are calculated by an integral ratio method. Results show that the air entrainment coefficient increases with fire heat release rates for a given ceiling extraction velocity, but decreases with increasing ceiling extraction velocities for a given heat release rate. A dimensionless factor $f(V)$ is introduced and the revised model of air entrainment coefficient under various ceiling extraction velocities is proposed. The entrainment coefficient for smoke flows in tunnel fires is found to be a function of the Richardson number. All the experimental data are well correlated by the new proposed model for the air entrainment coefficient with a single-point extraction system. This study proposes new empirical entrainment design formulae of tunnel fires under the effect of point ceiling extraction system.

1. Introduction

Tunnel thermal disasters have significantly increased because of the rapid development of urban tunnels in recent years. Such disasters can lead to catastrophic loss of human lives and properties [1,2]. In case of fire, the buoyancy-induced smoke flow behavior of ceiling jets has been widely investigated and reported [3–9], including the effect of natural ventilation [10–13] and mechanical smoke exhaust [14–17]. For example, Gong et al. [3] presented a theoretical analysis of heat transfer and mass transfer during the downward smoke movement in tunnel fires. Ang et al. [5], conducted simulations to investigate the longitudinal ventilation flows in long tunnels. Baek et al. [7] studied the impact of fire heat release rate (HRR) and tunnel aspect ratio on the plug-holing phenomenon in shallow underground tunnels. Zhong et al. [12] experimentally studied ceiling temperature profiles in a full-scale sloped long and large curved underground tunnel; it was found that the smoke movement is influenced by both fire HRRs and natural wind pressures. Vauquelin and Megret [17] investigated the smoke extraction efficiency of a transverse ventilation system. It was found that, for a given value of efficiency, the absolute extraction volume flow rate increases with HRR, whereas the relative extracting volume flow rate decreases.

Physically, as shown in Fig. 1, the process of smoke movement underneath the tunnel ceiling can be divided into four stages [4,18,19]: (a) driven by buoyancy stage, the smoke would freely move up to the tunnel ceiling; then (b) the smoke radially spreads beneath the tunnel ceiling and (c) follows a transition stage between the radial and one-dimensional horizontal movement due to the limitation of tunnel side walls; (d) finally the smoke would move one-dimensionally along the transverse direction of tunnel.

For one-dimensional steady movement stage, the differential increment in smoke mass was obtained in relation to the entrainment coefficient by Kunsch [18,19] as:

$$d\dot{m} = \beta \cdot \rho_a \cdot \omega \cdot \Delta u \cdot dx \tag{1}$$

where Δu denotes the relative velocity between the upper smoke layer and lower air layer at horizontal position x.

Hinkley [20] studied the smoke movement along a tunnel ceiling, showing that velocity decay can be proposed exponentially as:

$$u_s = u_{s0} \cdot \exp[\alpha(x_0 - x)] \tag{2}$$

Where u_{s0} denotes the smoke velocity at position x_0; and u_s denotes the smoke velocity at position x. Furthermore, in the State Key Laboratory

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Nomenclature

dm	Variable entrainment air mass rate, kg/s
dx	Position in section, m
G	Gravitational acceleration, m/s^2
h_s	Thickness of smoke layer at x, m
h_{s0}	Thickness of smoke layer at x_0, m
H	Height of tunnel, m
H_{int}	Height of smoke layer interface, m
r_l	Integral ratio of lower air layer
r_{to}	Total integral ratio
r_u	Integral ratio of upper Smoke layer
T_a	Air temperature, K
T_s	Smoke temperature at x, K
T_{s0}	Smoke temperature at x_0, K
u_s	Smoke velocity at x, m/s
V	Exhaust rate
V^*	Non-dimensional exhaust rate
u_{s0}	Smoke flow velocity at x_0, m/s
x	Position x in the axis, m
x_0	Position x_0 in the axis, m

Greek symbols

α	Multi-parameter combination variable
β	Entrainment coefficient
ρ_a	Air density, kg/m^3
ω	Width of tunnel, m
Δu	Relative velocity between the smoke layer and air layer, m/s

of Fire Science (SKLFS) of China, Wang et al. [21] developed the entrainment coefficient expressions for one-dimensional smoke movement stage without the effect of ceiling point extraction, indicating that the entrainment coefficient is determined by the ambient temperature, smoke flow velocity, smoke temperature and smoke layer thickness between the reference positions. Ding and Quintiere [22] proposed an integral model for turbulent flame radial lengths; this model used an empirical relationship for the mixing ratio of air entrained to the stoichiometric-air required for the ceiling jet-flame.

However, we note that the above findings are focused on the entrainment coefficients of a one-dimensional smoke movement stage in a tunnel under natural ventilation. As we know, mechanical ventilation will affect the smoke transport behavior [23–25]. Currently, the mechanical ventilation is widely applied in tunnel ceilings, and ceiling extraction can affect the smoke back-layering flow length, smoke temperature and thickness of smoke layers [26–32]. However, there is still no reported study on a tunnel fire showing the effect of point ceiling extraction system on the entrainment coefficient of a one-dimensional smoke movement stage in a ventilation tunnel. The entrainment in tunnel fires, including the ceiling extraction system effect, needs to be investigated further.

The aim of this study is to investigate the air entrainment coefficient during the one-dimensional plume horizontal movement stage of fire-induced smoke with the effect of point ceiling extraction by a series of scale model tunnel fire tests. In this study, the flame does not touch the tunnel ceiling. The smoke spreading beneath the ceiling in the ventilation tunnel was induced by a weak plume.

Table 1
Summary of experimental conditions.

Test no.	HRR (kW)	Ceiling extraction velocity (m/s)			
1–4	1.5	0	0.5	1.5	2.5
5–8	2.25	0	0.5	1.5	2.5
9–12	3.0	0	0.5	1.5	2.5
13–16	3.75	0	0.5	1.5	2.5
17–20	4.5	0	0.5	1.5	2.5

2. Experimental section

2.1. Experiment rig

To investigate the fire-induced air entrainment behavior for a one-

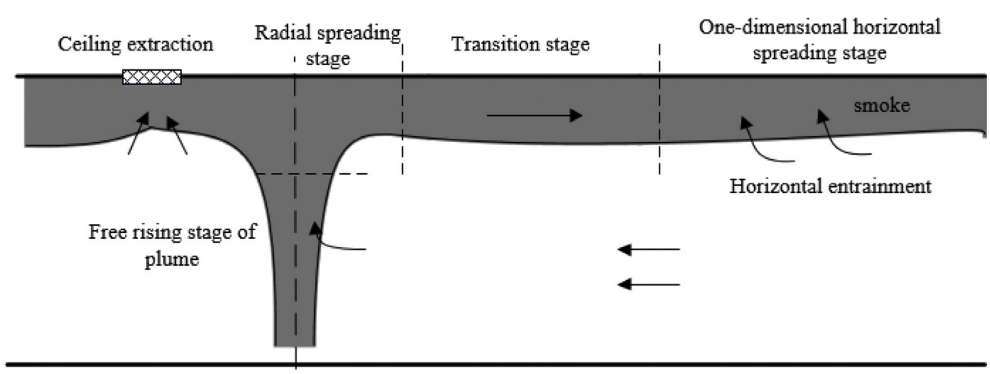

Fig. 1. Smoke movement in tunnel fires.

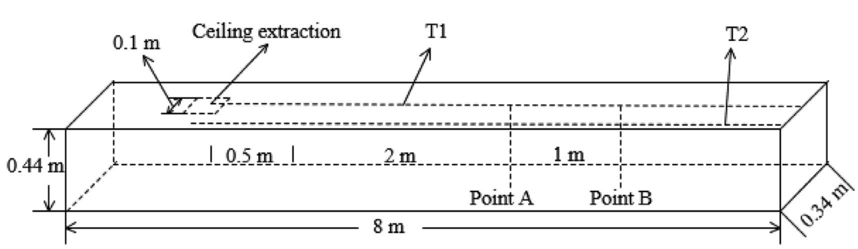

Fig. 2. Schematic of scale model tunnel.