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Study on induced airflow velocity of point smoke extraction in road tunnel fires

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ABSTRACT

In the point smoke extraction system, induced airflow velocity which can restrain smoke back-layering is an important parameter to evaluate smoke control efficiency of smoke extraction systems. New formula for the induced airflow velocity and smoke back-layering length is proposed for the tunnel fires with different heat release rates through small-scale tunnel model experiments. The experiment results show that when the dimensionless back-layering length is more than four, the influence of smoke outlet area on the induced airflow velocity and smoke back-layering length can be negligible. The relationship between the dimensionless back-layering length and induced airflow velocity is greatly affected by the heat release rate. In point extraction system, the smoke back-layering length increases gradually with the increasing of heat release rate, then tends to be smooth.

1. Introduction

Point smoke extraction is conducting mechanical extraction by opening outlets around both sides of fire source in tunnel fires. Due to suction effect of axial flow fans on both sides, the extraction duct forms huge negative pressure, pushing smoke to flow towards outlets. The airflow velocity posed by mechanical smoke extraction around outlets is called induced airflow velocity which can restrain smoke back-layering and is a crucial parameter to measure the smoke control of extraction systems. Smoke back-layering length in point smoke extraction mode refers to a phenomenon, in which smoke crawled past outer outlets. Back-layering length can be defined as the distance from outer outlets to the edge of smoke movement. When smoke is controlled inside outer outlets, back-layering length of smoke can extend a length of 0 m. Induced airflow velocity at the time is called absolute confinement airflow velocity. If smoke back-layering length is equal to four times the height of tunnel, the induced airflow velocity will be called confinement airflow velocity (Vauquelin and Telle, 2005) and (Xie, 2006).

The relationship between airflow velocity and back-layering length has been a focus study for researchers (Zhang et al., 2016a,b; Yi et al., 2014; Wu and Baker, 2000; Roh et al., 2007; Yang et al., 2010; Chen et al., 2013; Tsai et al., 2011). For example, Li et al. (2010) investigated the critical velocity together with the back-layering length in tunnel fires through experimental tests and theoretical analyses, and found the relation between the ratio of ventilation velocity to critical velocity and the dimensionless back-layering length follows an exponential relation. Kang (2010) examined the effects of enclosure blockage ratio and tunnel width or aspect ratio on critical ventilation velocity using numerical modeling. Danziger and Kennedy (1982) and Kennedy and Parsons (1996) derived a semi-empirically equation to calculate the critical velocity by relating the temperature rise of hot gases from a fire to the convective heat release rate from the fire. The relational equations of dimensionless back-layering length and vertical ventilation airflow velocity in conditions of different tunnel section coefficients have been studied by Weng et al. (2016). Based on CFD simulation and small-scale experiments, Weng et al. (2015) proposed a prediction model for the back-layering length in metro tunnel fires. Wang et al. (2016) researched the influence of tunnel shaft on smoke back-layering length and deduced a formula to calculate smoke back-layering length and airflow velocity in tunnel shaft, and verified it through experiments. Model scale tunnel fire tests with point extraction were also made (Ingason and Li, 2011). Xu et al. (2012) evaluated and compared the smoke control strategy under five different induced velocities, the results showed that larger induced velocity is needed to restrict smoke. Some scholars have studied the ventilation system of the tunnel in order to control the fire smoke and presented some new ventilation models (Y.Z. Li et al., 2016; L.J. Li et al., 2016; Cascetta et al., 2016; Mao and Yang, 2016). The smoke back-layering flow length is also investigated under different circumstances (Yao et al., 2016; Tang et al., 2016;

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Nomenclature

A	tunnel cross-sectional area (m^2)
c_p	specific heat of air at constant pressure (kJ/kg·K)
g	gravitational acceleration (m/s^2)
H	tunnel height (m)
L	smoke back-layering length (m)
Q	heat release rate (kW)
T_a	ambient air temperature (K)
v_{in}	induced airflow velocity (m/s)
S	smoke outlet area (m^2)
a_0	the long side of rectangle outlet (m)
b_0	the short side of rectangle outlet (m)
ρ_a	ambient air density (kg/m^3)
Q^*	dimensionless heat release rate
$v_{in}{}^*$	dimensionless induced airflow velocity
S^*	dimensionless smoke outlet area
L^*	dimensionless smoke back-layering length
Fr	Froude number
d	tunnel width (m)
h	smoke layer thickness (m)
$\bar{h}$	characteristic length of the smoke layer (m)
v	average smoke velocity (m/s)
x	the longitudinal distance form outlet (m)
v_x	airflow velocity at x distance form outlet (m/s)
v_0	airflow velocity in outlet (m/s)

Zhang et al., 2016a,b). Through a series of fire test in a model tunnel (1:10), dimensionless back-layering length was found decreased with the increase of the dimensionless ventilation velocity nearly linearly (Yi et al., 2013). Xu and Zhang (2008) studied the effect of smoke outlet characteristics on smoke control for highway tunnel with central smoke extraction systems. Y.Z. Li et al. (2016) and L.J. Li et al. (2016) have studied the smoke thermal stratification with ceiling extraction in a longitudinal ventilated tunnel through a series of experiments with a 1/6 scale model tunnel.

All the study above investigated the longitudinal ventilation velocity or smoke back-layering flow length through numerical simulation or model experiments. However, there were little study about the influence of smoke outlet area on the induced airflow velocity. In addition, different fire sources (cold smoke and hot smoke) may lead to huge deviation among research results. This paper uses bench-scale model to research the relationship between the smoke back-layering length and the induced airflow velocity which is influenced by the heat release rate, the volume of smoke extraction and the smoke outlet area. With the increase of the induced airflow velocity, the smoke back-layering length is reduced, it is the important index to measure the effect of the smoke control system. In addition, it is similar to the critical velocity which is important to control smoke flow. In order to facilitate the engineering application, the coupling relationship between the three is determined by experiments. Based on the experiment, the optimal design of the smoke extraction system is made, and the reasonable longitudinal induced airflow velocity is determined.

2. Analysis of the relationship between induced airflow velocity and smoke back-layering length

Fig. 1 displays induced airflow velocity in a point extraction system. Vauquelin and Telle (2005) conducted cold smoke experiments about the point extraction system in a scale model of 1:20 and revealed it was acceptable to control the back-layering length within a scope of $L \le 4H$ from the perspective of economical efficiency and safety.

The governing parameters for induced airflow velocity are the heat release rate, the smoke back-layering length, the tunnel height, the air density, the ambient temperature, the thermal capacity of air and the gravitational acceleration. Similarly, the induced airflow velocity can be expressed as:

$$v_{in} = f(Q,L,\rho_a,T_a,c_p,g,H) \tag{1}$$

The L, T, M and θ are selected as the basic dimensions, and the H, v, ρ_a and c_p are selected as the basic parameters, then the dimensionless equations for the other four parameters can be expressed as below:

$$\begin{cases} \pi_1 = \bar{H}^{\alpha_1} v^{\beta_1} \rho_a^{\gamma_1} c_p^{\varepsilon_1} L = L^{\alpha_1}[LT^{-1}]^{\beta_1}[ML^{-3}]^{\gamma_1}[L^2T^{-2}\theta^{-1}]^{\varepsilon_1} L \\ \pi_2 = \bar{H}^{\alpha_2} v^{\beta_2} \rho_a^{\gamma_2} c_p^{\varepsilon_2} Q = L^{\alpha_2}[LT^{-1}]^{\beta_2}[ML^{-3}]^{\gamma_2}[L^2T^{-2}\theta^{-1}]^{\varepsilon_2}[ML^2T^{-3}] \\ \pi_3 = \bar{H}^{\alpha_3} v^{\beta_3} \rho_a^{\gamma_3} c_p^{\varepsilon_3} T_a = L^{\alpha_3}[LT^{-1}]^{\beta_3}[ML^{-3}]^{\gamma_3}[L^2T^{-2}\theta^{-1}]^{\varepsilon_3}\theta \\ \pi_4 = \bar{H}^{\alpha_4} v^{\beta_4} \rho_a^{\gamma_4} c_p^{\varepsilon_4} g = L^{\alpha_4}[LT^{-1}]^{\beta_4}[ML^{-3}]^{\gamma_4}[L^2T^{-2}\theta^{-1}]^{\varepsilon_4}[LT^{-2}] \end{cases} \tag{2}$$

The indexes of the physical quantities can be solved by the conservation principle:

$$\begin{cases} \alpha_1 = -1, \beta_1 = \gamma_1 = \varepsilon_1 = 0 \\ \alpha_2 = -2, \beta_2 = -3, \gamma_2 = -1, \varepsilon_2 = 0 \\ \alpha_3 = 0, \beta_3 = -2, \gamma_3 = 0, \varepsilon_3 = 1 \\ \alpha_4 = 1, \beta_4 = -2, \gamma_4 = \varepsilon_4 = 0 \end{cases} \tag{3}$$

So the dimensionless equations can be simplified as bellow:

$$\begin{cases} \pi_1 = \bar{H}^{-1} L = \frac{L}{\bar{H}} \\ \pi_2 = \bar{H}^{-2} v^{-3} \rho_a^{-1} Q = \frac{Q}{\rho_q \bar{H}^2 v^3} \\ \pi_3 = v^{-2} c_p T_a = \frac{c_p T_a}{v^2} \\ \pi_4 = \bar{H} v^{-2} g = \frac{g\bar{H}}{v^2} \end{cases} \tag{4}$$

Considering the influence of outlet area on induced airflow velocity and smoke back-layering length, this paper defines dimensionless outlet area as the following:

$$S^* = S/A \tag{5}$$

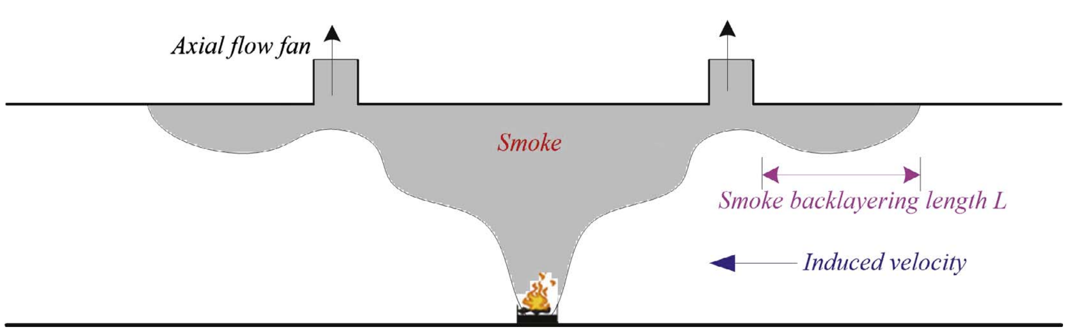

Fig. 1. Sketch of induced airflow velocity in point extraction system.