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Research Paper

Study on the critical velocity in a sloping tunnel fire under longitudinal ventilation

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HIGHLIGHTS

- The sectional coefficient ζ was introduced to describe the tunnel cross section.
- The dimensionless backlayering length and critical velocity were proposed.
- Two hundred fifty simulations based on nine typical tunnels were carried by FDS.
- Forty-five small-scale model experiments were carried out in a 1/10 scale model tunnel.
- The slopes of the tunnels in simulations and tests were from −3% to 3%.

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ABSTRACT

The critical velocity and the backlayering length of smoke in tunnel fires are the two most important parameters in longitudinal ventilation design. This paper deduced the dimensionless expression of backlayering length and critical velocity of smoke in tunnel fires using the dimensional analysis method. The sectional coefficient ζ ($\zeta = A/H^2$) was introduced to describe the geometrical characteristic of the tunnel section, and the characteristic hydraulic diameter of the tunnel $\bar{H}$ replaced the tunnel height H. Then, CFD simulations were conducted in nine tunnels with different cross sectional shapes using the proprietary software Fire Dynamic Simulator (FDS), version 5.5. With the FDS simulations, prediction models for backlayering length and critical velocity modified by the sectional coefficient ζ and the tunnel slope were proposed. Meanwhile, complementary experiments were carried out in a 1/10 scale tunnel in order to provide a verification. The experimental results show a good agreement with the numerical simulations. Moreover, the prediction models for critical velocity on different slopes were compared with the prediction models proposed by others.

1. Introduction

The reverse flow of smoke in tunnel fires is one of the special smoke movements in longitudinal ventilation. The critical velocity is the minimum longitudinal ventilation velocity to prevent the reverse flow of the smoke from the fire in the upstream direction in the tunnel. The backlayering length is the length of the reversed smoke front along the upstream direction to the fire source when the ventilation velocity is lower than the critical velocity. The critical velocity is the longitudinal ventilation velocity when the backlayering length is zero. There is no smoke to the upstream direction of the fire source when the longitudinal velocity is greater than the critical velocity in the tunnel. Thus, it can prevent the hazards of smoke to blocked vehicles and personnel of the upstream direction, and also provide safe passage for the aid to firefighters. The critical velocity involves many factors, such as fire scale, slope and tunnel cross-section geometry, etc. Among them, the fire scale has the greatest impact on the critical velocity [1]. The critical velocity has been a focus of study of researchers from various countries [2,3].

Based on the theoretical analysis, Thomas [4] proposed a prediction model for the backlayering length in case of a fire in a longitudinally ventilated tunnel. The equation of the predicted model is shown as follows:

$$L^* = \frac{L}{H} \propto \frac{gHQ}{\rho_a T_f C_p V^3 A} \tag{1}$$

Vantelon et al. [5] carried out small-scale experiments in a 1.5 m long semicircular pipe with 0.15 m radius. Their research showed

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that the dimensionless backlayering length is related to the modified Richardson number as the following formula:

$$L^* \propto Ri'^{0.3} \tag{2}$$

where $Ri' = \dfrac{gQ}{\rho_a T_a C_p V^3 H}$.

Li et al. [6] proposed the following equation for the dimensionless backlayering length based on theoretical analysis and small-scale experiments.

$$L^* = \begin{cases} 18.5\ln\left(0.81 Q^{*1/3}/V^*\right) & Q^* \le 0.15 \\ 18.5\left(0.43/V^*\right) & Q^* > 0.15 \end{cases} \tag{3}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2}}$, $V^* = \dfrac{V}{(gH)^{1/2}}$.

Based on CFD simulations and small-scale experiments, Weng et al. [7] proposed a prediction model for the backlayering length in metro tunnel fires.

$$\frac{L}{\bar{H}} = 7.13\ln\left(\frac{Q^*}{V^{*3}}\right) - 4.36 \tag{4}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} \bar{H}^{5/2}}$, $V^* = \dfrac{V}{(g\bar{H})^{1/2}}$.

In addition to the work of these researchers there is a great deal of theoretical, numerical and experimental studies on critical velocity that can be found in literature.

Thomas [8] suggested a predicted model for the critical velocity of longitudinal ventilation based on the theory of the Froude number, which is shown as the following formula:

$$V_c = k\left[\frac{gQ'}{\rho_a C_p T_f}\right]^{1/3} \tag{5}$$

where k is a constant. The value of k was determined from suitable experiments.

Kennedy and co-workers [9,10] derived a semi-empirical 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. This is stated as follows:

$$V_c = k_g k'\left[\frac{gHQ}{\rho_a C_p A T_f}\right]^{1/3} \tag{6}$$

$$T_f = \frac{Q}{\rho_a C_p A V_c} + T_a$$

where k' is a constant which is set to 0.61. When the fire occurs on a horizontal or uphill tunnel $k_g = 1.0$, and $k_g = 1.0 + 0.0374(\tan\theta)^{0.8}$ when the fire occurs on a downhill tunnel, where $\tan\theta$ is the tangent of the slope angle (%).

Oka and Atkinson [11] carried out a series of small-scale experiments to examine the relationship between the critical velocity and the heat release rate, taking different geometries of the fire source into account. A dimensionless equation was proposed:

$$V_c^* = \begin{cases} k_v\left(\dfrac{Q^*}{0.12}\right)^{1/3} & Q^* < 0.12 \\ k_v & Q^* \ge 0.12 \end{cases} \tag{7}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2}}$, $V^* = \dfrac{V}{(gH)^{1/2}}$. And k_v is a constant that varies from 0.22 to 0.38.

Wu and Bakar [12] carried out another series of small-scale experimental tests in five model tunnels to investigate the effect of tunnel geometry on the critical velocity, where the model tunnels had the same heights but different widths. Likewise, a prediction model between the dimensionless heat release rate and dimensionless critical velocity was proposed:

$$V^* = \begin{cases} 0.4\left(\dfrac{Q^*}{0.20}\right)^{1/3} & Q^* \le 0.20 \\ 0.4 & Q^* > 0.20 \end{cases} \tag{8}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} \bar{H}^{5/2}}$, $V^* = \dfrac{V_c}{(g\bar{H})^{1/2}}$.

Li et al. [6] proposed prediction models of the critical velocity in tunnel fires based on experimental results and theoretical analysis.

$$V^* = \begin{cases} 0.81(Q^*)^{1/3} & Q^* \le 0.15 \\ 0.43 & Q^* > 0.15 \end{cases} \tag{9}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2}}$, $V^* = \dfrac{V_c}{(gH)^{1/2}}$.

Weng et al. [7] also proposed a prediction model for critical velocity by 1/10 scale model experiments and CFD simulations.

$$V_c^* = 0.82 Q^{*1/3} \tag{10}$$

where $Q^* = \dfrac{Q}{\rho_a C_p T_a g^{1/2} \bar{H}^{5/2}}$, $V^* = \dfrac{V}{(g\bar{H})^{1/2}}$.

Most tunnels have a slope which can significantly affect smoke movement under fire due to buoyancy and stack effects. After the study of Oka and Atkinson [11], Atkinson and Wu [13] carried out experimental study on the critical velocity to show how this was changed by the tunnel slope and suggested the following relationship to consider the slope of inclined tunnel based on the critical velocity in the horizontal tunnel.

$$V_{C,\theta}/V_{C,0} = (1 + 0.014\theta) \tag{11}$$

Ko et al. [14] used experimental study to investigate the effects of a tunnel slope on the critical velocity in the tunnel fires. The relationship between the normalized critical velocity and the angle of tunnel slope was determined as:

$$V_{C,\theta}/V_{C,0} = (1 + 0.033\theta) \tag{12}$$

Based on experiment results, Yi et al. [15] proposed the correlation between the critical velocity and the tangent of the slope angle of the tunnel expressed as:

$$V_{C,\beta}/V_{C,0} = (1 + 0.034\beta) \tag{13}$$

Chow et al. [16] studied on smoke movement in a tilted tunnel fire with longitudinal ventilation, and an equation was produced in terms of the angle of tilt θ:

$$V_{C,\theta}/V_{C,0} = (1 + 0.022\theta) \tag{14}$$

A recent model tunnel has been built [7] with which experiments on tunnel ventilation and smoke extraction were carried