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Effect of ceiling centralized mechanical smoke exhaust on the critical velocity that inhibits the reverse flow of thermal plume in a longitudinal ventilated tunnel

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ABSTRACT

Toxic fire smoke in a tunnel fire is an important factor causing casualties. The critical ventilation velocity that inhibits reverse transportation of toxic thermal smoke in a longitudinal ventilated tunnel is an important design parameter. The evolution characteristics of the critical velocity in a tunnel with the coupling effect between ceiling centralized mechanical smoke exhaust and longitudinal ventilation have never been studied before. A series of small scale tunnel experiments were conducted, ten different ceiling mechanical exhaust rates (0–2.7 m/s) and twelve fire heat release rates (1.5–18 kW) are considered. It is found that, the ceiling centralized mechanical smoke exhaust will affect the critical velocity that inhibits the reverse flow of smoke in a tunnel. Due to the effect of ceiling mechanical smoke exhaust, the critical velocity decreases with increasing mass flow rates of mechanical smoke exhaust. The critical Froude number increases with increasing exhaust mass flow rate for a given dimensionless fire heat release rate. A new empirical model for predicting the critical ventilation velocity with the coupling effect between ceiling centralized mechanical smoke exhaust and longitudinal ventilation is proposed, which agree well with the measurement.

1. Introduction

1.1. Background and literature review

The traffic tunnel is a long and narrow space. Lots of toxic and harmful thermal smoke induced by tunnel fire can cause heavy casualties (Lin et al., 2008; Oh et al., 2010; Chow et al., 2010; Barbato et al., 2014; Harish and Venkatasubbaiah, 2014; Du et al., 2015; Giachetti et al., 2017; Król et al., 2017; Cong et al., 2017; Gao et al., 2016). Previous studies have mainly focused on smoke flow in ventilated tunnel, including (a) longitudinal temperature decay (Hu et al., 2008; Li et al., 2014; Zhao et al., 2015; Oka et al., 2016; Wang and Wang, 2016; Zhong et al., 2016; Liu et al., 2017; Tanaka et al., 2017; Zhou et al., 2017; Wang et al., 2018a; Meng et al., 2018); (b) maximum temperature profile (Hu et al., 2006; Li et al., 2011; Gao et al. 2014; Huang et al., 2017; Zhang et al., 2017a); at the same time, the impingement thermal plume will spread along the tunnel, effectively preventing the reverse flow of thermal plume is a very important design parameter of smoke control. The reverse flow of thermal plume will occur upstream when the longitudinal ventilation velocity is not high enough. With the increasing longitudinal ventilation velocities, the reverse flow of thermal plume (the smoke back-layering flow length) will gradually reduce until it disappears, the critical velocity is defined as the minimum longitudinal ventilation velocity, preventing the smoke reverse flow from a fire source in the tunnel (Ko et al., 2010; Li et al., 2010, Tsai et al., 2011; Lee and Tsai, 2012; Tang et al., 2013; Yi et al., 2014; Gannouni and Maad, 2015; Weng et al., 2016; Li and Ingason, 2017). This is the velocity needed to prevent smoke back-layering at a certain position, that is, to prevent further spreading upstream. It also can ensure no smoke upstream and provide a safe escape environment (Hu et al., 2008; Ingason et al., 2015b; Tang et al., 2016; Fan and Yang, 2017; Tang et al., 2017; Ko and Hadjisophocleous, 2013; Yao et al., 2016; Yu et al., 2016; Wu et al., 2018; Wang et al., 2018b).

Many previous works have been done to investigate the critical velocity in the longitudinal ventilation tunnel under different conditions (Thomas, 1958, 1968; Oka and Atkinson, 1995; Wu and Baker, 2000; Lee and Ryou, 2006; Ko et al., 2010; Li et al., 2010, Tsai et al., 2011; Lee and Tsai, 2012; Tang et al., 2013; Yi et al., 2014; Gannouni and Maad, 2015; Weng et al., 2016; Li and Ingason, 2017; Li and Ingason, 2018).

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Nomenclature

A	cross-sectional area of the tunnel, m^2
c_p	thermal capacity of air, kJ/(kg K)
Fr_c	critical Froude number
g	gravitational acceleration, m/s^2
H	height of the tunnel, m
$\overline{H}$	hydraulic tunnel height, m
K_V	constant
ℓ_F	length scale of actual-size experimental study
ℓ_M	model length scale of actual-size experimental study
$\dot{m}$	mass flow rate
Q	heat release rate, kW
Q_a	actual heat release rate, kW
Q^*	dimensionless heat release rate
Q^{**}	dimensionless heat release rate with ceiling smoke extraction
$Q_{c,F}$	heat release rate of actual-size tunnel
$Q_{c,M}$	heat release rate of model tunnel
S	extraction opening area, m^2
T	smoke temperature, K
T_a	ambient air temperature, K
$\Delta T_{\max}$	maximum excess smoke temperature, K
V	ceiling extraction velocity, m/s
V_c	the critical velocity, m/s
V_c^*	dimensionless critical velocity
V_c^{**}	dimensionless critical velocity with ceiling smoke extraction
v^*	actual critical velocity with ceiling smoke extraction, m/s
W	width of the tunnel, m

Greek symbols

ρ	smoke density, kg/m^3
ρ_0	ambient air density, kg/m^3
$\Delta\rho$	density difference, kg/m^3
ζ	cross sectional coefficient

1.2. Previous basic model

Thomas (1958, 1968) proposed the critical Froude number to describe the critical velocity, and he found that the smoke back-layering flow length disappeared when the critical Froude number is close to 1:

$$Fr_c = \frac{\Delta\rho g H}{\rho_0 V_c^2} \tag{1}$$

Oka and Atkinson (1995) conducted a series of scale model tunnel (1:10 model tunnel) experiments for critical velocity. The propane is used as the fire source, the effect of changes in the fire shape, fire size and its location on the critical velocity have been studied. Finally, it is found that critical velocity of tunnel fire is almost unchanged when the fire heat release rate (HRR) got a certain amount. The critical velocity model under different burner sizes is proposed:

$$V_c^* = \begin{cases} K_V\left(\dfrac{Q^*}{0.12}\right)^{1/3} & Q^* \leqslant 0.12 \\ K_V & Q^* > 0.12 \end{cases} \tag{2}$$

where

$Q^* = \frac{Q}{\rho_0 c_p T_a \sqrt{g H^5}}$, $V_c^* = \frac{V_c}{\sqrt{gH}}$

K_V is the value obtained experimentally, its value depends on burner size and position, respectively, between 0.22 and 0.38.

Wu and Bakar (2000) conducted experiments with different cross sections of the tunnel. They proposed the predicted critical velocity model with different cross sections of tunnel, where the concept of the tunnel hydraulic diameter was introduced to replace the tunnel height. The Wu and Bakar's (Wu and Bakar, 2000) correlation is as follows:

$$V_c^* = \begin{cases} 0.4\left(\dfrac{Q^*}{0.2}\right)^{1/3} & Q^* \leqslant 0.2 \\ 0.4 & Q^* > 0.2 \end{cases} \tag{3}$$

where

$Q^* = \frac{Q}{\rho_0 c_p T_a \sqrt{g\overline{H}^5}}$, $V_c^* = \frac{V_c}{\sqrt{g\overline{H}}}$

The equation of tunnel hydraulic diameter is as follows:

$$\overline{H} = 4\frac{A}{X} = 2\frac{WH}{(W+H)} \tag{4}$$

where W is the tunnel width, and H is the tunnel height.

In 2010, Li et al. (2010) conducted many experiments and proposed critical velocity model:

$$V_c^* = \begin{cases} 0.81 Q^{*1/3} & Q^* \leqslant 0.15 \\ 0.43 & Q^* > 0.15 \end{cases} \tag{5}$$

where

$Q^* = \frac{Q}{\rho_0 c_p T_a \sqrt{g H^5}}$, $V_c^* = \frac{V_c}{\sqrt{gH}}$

In 2012, Lee and Tsai investigated the critical velocity in a longitudinal ventilated tunnel with different vehicular blockage ratio. It is found that the critical velocity in a tunnel reduced with the increasing blockage ratio of vehicle. The reduction ratio is nearly equal to the blockage ratio of vehicle. Tang et al. (2013) studied the effect of blockage-fire distance on the critical velocity in a model tunnel, it is found that, the critical velocity decreased firstly, and then it maintained to be constant with increasing distance between vehicular blockage and fire source. Yi et al. (2014) investigated critical velocity in 1/10 scale model longitudinal ventilation tunnel with the change of sloping angle of tunnel. It is found that, the critical velocity decreased with the increasing sloping angle of the tunnel from −3% to 3%. Weng at al. (2016) proposed new dimensionless critical velocity correlation for the tunnels with different cross sectional coefficients and sloping angle.

1.3. Goal of this work

However, we note that above findings focused on critical velocities under the effect of longitudinal ventilation and other geometric features of tunnels. Recently, this combined ventilation strategy between ceiling centralized mechanical smoke exhaust and longitudinal ventilation is often used in long and large tunnels in China, such as, Wuhan Yangtze river tunnel, Nanjing Yangtze river tunnel, etc. Our China's national regulations《Guidelines for Design of Ventilation of Highway Tunnel》(JTG/T D70/2-02-2014), clearly gives the definition of critical velocity and the recommendations of critical velocity under the control system of longitudinal ventilation tunnel fires. For example, for the design of HRR = 20 MW in longitudinal ventilation tunnel fires, the critical velocity is recommended as about 2–3 m/s.

It should be noted that, these critical velocities depend on many factors, such as tunnel section size, ventilation strategy, slope and fire scale, etc. For the combined ventilation strategy mode, China's national regulations does not give the suggestion value of critical velocity.

As the centralized mechanical ventilation is widely applied in a tunnel ceiling, the ceiling centralized mechanical exhaust can affect the smoke spread characteristics (Ingason and Li, 2011; Chen et al., 2013; Hu et al., 2014; Li et al., 2016; Yang and Chuah, 2017; He et al., 2018). The addition of centralized smoke exhaust will exhaust a part of smoke and heat, and will induce longitudinal ventilation velocity, thus affect the critical velocity.

There is still no work reported about this tunnel fire to reveal the effect of mechanical smoke exhaust on the critical velocity. So it is

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