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Effect of cross section on critical velocity in longitudinally ventilated tunnel fires

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ABSTRACT

Numerical and theoretical work was conducted to investigate the effect of tunnel cross section on critical velocity for smoke control in longitudinally ventilated tunnel fires. The results show that for small fires, the critical velocity decreases with both the increasing tunnel height and tunnel width. For large fires, the critical velocity significantly increases with the increasing tunnel height but is independent of tunnel width. Different calculation models are compared with a focus on effect of tunnel cross section. A new correlation is proposed to account for the effect of tunnel width based on the previous model.

1. Introduction

Nowadays most tunnels use longitudinal ventilation systems. In case of a fire, a longitudinal air flow is produced to prevent the smoke from spreading upstream. The minimum longitudinal ventilation velocity to prevent reverse flow of smoke from a fire in the tunnel is defined as the critical velocity (see Fig. 1). The critical velocity is one of the most investigated parameters in tunnel fire community [1–9]. Recently there are some researches on effect of blockage on smoke control [9–11], e.g. due to appearance of vehicles nearby or the burning vehicle itself, and effect of fire source location [12].

At the evacuation stage in case of a tunnel fire, control of smoke backlayering assures smoke clear path for personnel upstream of the fire. At the fire fighting stage, this measure provides access to the fire site for fire fighters.

The effect of tunnel cross section on critical velocity has also attracted some attention. In this paper tunnel aspect ratio (*AR*) is defined as the ratio of tunnel width to height ($AR=W/H$). For tunnel cross sections of arcuate shape, the width could be approximately estimated by the area divided into tunnel height ($W=A/H$). Note that the tunnel aspect ratio is generally in a range of 1–6, and mostly 1–3.

There has been some experimental work on the influence of tunnel width on the critical velocity. Wu and Bakar [6] carried out a series of tests in model tunnels with aspect ratios from 0.5 to 4.0. They correlated their results using the hydraulic diameter instead of the tunnel height. Vauquelin and Wu [13] further investigated the influence of tunnel width on the critical velocity. The results of cold gas tests using a mixture of helium and air to simulate the hot gases and results from Wu and Bakar's tests [6] were analyzed. It was found that in both series of tests, for aspect ratios greater than unity, it is noticed that the critical velocity decreases when the width increases. They also found that for the aspect ratio lower than one and for high enough HRRs, the critical velocity increases with tunnel width. The reason is that for a very narrow tunnel the fire plume intersects the tunnel walls and thus the plume properties are not the same. This, however, is not the case for vehicle tunnels of main concern in the present work with an aspect ratio of 1–6. It should be kept in mind that in Wu and Bakar's [6] tests, the use of water sprays in the vicinity of the fire source could result in large error, especially when the tunnel is very wide, and in Vauquelin's tests [13] the cold gas was used which could differ significantly from a realistic fire. Lee and Ryou [14] conducted model scale ethanol pool fire tests in tunnels of different aspect ratios and proposed a correlation similar to Wu and Barkar's for small fires. The heat release rates (HRRs) in the tests with ventilation are assumed to be the same as that in the tunnel with an aspect ratio of 1 and no ventilation. This may not be true as the ventilation could have significant influence on burning rates of small pool fires [15]. The tunnel height could also affect their burning [16]. A similar scenario is the smoke control in car parks. Tilley and Merci [17] carried out a numerical study of smoke control in car park fires with longitudinal ventilation. They found that the critical velocity increases with the increasing tunnel height and decreases slightly with the increasing tunnel width. A correlation was proposed but it may only be suitable for the scenarios simulated but not for tunnel fires.

The main objective of this paper is to investigate the effect of tunnel cross section on critical velocity for smoke control in longitudinally ventilated tunnel fires. Further, for practical use, different calculation models are compared and analyzed with a focus on the effect of cross

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Nomenclature

A	tunnel cross-sectional area (m^2)
c_p	thermal capacity of air (kJ/kg K)
C_1	coefficient
C_2	coefficient
Fr_c	critical Froude Number
g	gravitational acceleration (m/s^2)
h	smoke layer depth (m)
H	tunnel height (m)
$\overline{H}$	hydraulic diameter (m)
Q	heat release rate (kW)
Q_c	convective heat release rate (kW)
Q^*	dimensionless heat release rate
$Q^*_{\overline{H}}$	dimensionless heat release rate based on hydraulic diameter
T_F	flame temperature (K)
T_o	ambient temperature (K)
ΔT_{max}	maximum ceiling excess gas temperature (K)
u	horizontal gas velocity (m/s)
u_c	critical velocity (m/s)
u_c^*	dimensionless critical velocity
$u^*_{c,\overline{H}}$	dimensionless critical velocity based on hydraulic diameter
W	tunnel width (m)

Greek

ρ_o	ambient density (kg/m^3)
ρ	smoke density (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)

section.

2. Calculation models

In practical applications, there are mainly two types of models to estimate the critical velocity, i.e. the critical Froude model and the non-dimensional models, where the effect of tunnel cross section is considered in various ways. In the following, a summary of these calculation models for critical velocity in tunnel fires is given.

2.1. Critical Froude model

The critical Froude model was proposed by Thomas [1,2] and use of a critical Froude number of 4.5 was proposed by Danziger and Kennedy [3,4] based on one data point from Lee et al.'s experimental work [18]. The critical Froude model was developed based on the assumption of full mixing between the heat and the incoming air flow immediately at the fire site. This cannot be true for a wide tunnel. In other words, the effect of tunnel geometry or tunnel aspect ratio on the critical velocity could not be well accounted for.

The critical Froude model for critical velocity can be expressed in the following form:

$$u_c = \left[\frac{gQ_c}{\rho_o c_p\left(\frac{Q_c}{\rho_o c_p H u_c} + T_o W\right)\mathrm{Fr}_c}\right]^{1/3} \quad (1)$$

In the above equation, Fr_c is the critical Froude number, which is considered as 4.5 by Danziger and Kennedy [3,4]. The above equation indicates that the critical velocity increases with the increasing tunnel height and decreases with tunnel width for a given heat release rate.

2.2. Oka and Atkinson's model

Oka and Atkinson [5] carried out a series of fire tests in one horse shape tunnel and tunnel height is used as the characteristic length in their model. The following equation for the critical velocity was proposed:

$$u_c^* = \begin{cases} 0.7Q^{*1/3} & Q^* \le 0.124 \\ 0.35 & Q^* > 0.124 \end{cases} \quad (2)$$

where the dimensionless critical velocity and dimensionless heat release rate are:

$$u_c^* = \frac{u_c}{\sqrt{gH}}, \quad Q^* = \frac{Q}{\rho_o c_p T_o g^{1/2} H^{5/2}}$$

The above equation indicates that the critical velocity decreases with the increasing tunnel heights for small fires ($Q^* < 0.124$) but increases with the increasing tunnel heights for large fires ($Q^* > 0.124$), and is independent of tunnel width.

2.3. Wu and Bakar's model

Based on a series of tests in model tunnels with aspect ratios (width/height) from 0.5 to 4.0, Wu and Bakar [6] correlated their results of critical velocity with the hydraulic diameter by the following equation:

$$u^*_{c,\overline{H}} = \begin{cases} 0.68Q^{*1/3}_{\overline{H}} & Q^*_{\overline{H}} \le 0.2 \\ 0.40 & Q^*_{\overline{H}} > 0.2 \end{cases} \quad (3)$$

where

$$u^*_{c,\overline{H}} = \frac{u_c}{\sqrt{g\overline{H}}}, \quad Q^*_{\overline{H}} = \frac{Q}{\rho_o c_p T_o g^{1/2}\overline{H}^{5/2}}$$

The effect of tunnel height is similar to that in Oka and Atkinson's model. The main difference is that, in this model, increasing tunnel width results in a lower critical velocity for small fires while a higher critical velocity for large fires.

2.4. Kunsch's model

Kunsch [7] conducted a theoretical analysis of smoke movement in a tunnel under no ventilation based on Alpert's theory of ceiling jets under unconfined ceilings [19], and proposed a simple mathematic equation for critical velocity. To propose the explicit solution, the energy equation for weak plumes was used, which could not be appropriate for large fires. Despite the theoretical weakness, the

Fig. 1. A diagram of critical velocity in a tunnel fire.