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Numerical study of the effect of blockage on critical velocity and backlayering length in longitudinally ventilated tunnel fires

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ABSTRACT

In a tunnel fire, one of the protective strategies of users and vehicles which are blocked upstream of fire is provided by longitudinal ventilation systems which serve to limit the rise of smoke flow (backlayering). The presence of these vehicles creates an obstruction which affects the plume fire behavior and the smoke movement. The longitudinal ventilation velocity from which the backlayering disappears, usually designated by "critical ventilation velocity", is a key parameter to ensure proper evacuation of users and emergency intervention. This study performs numerical simulation using Fire Dynamic Simulator (FDS) to estimate the effect of an obstacle blockage according to its location relative to the tunnel floor on the backlayering flow behavior and the critical velocity. An obstacle occupying about 31% of the tunnel cross section is placed symmetrically upstream of fires by changing its location relative to the tunnel floor. The validity of the FDS Numerical results is firstly demonstrated through a comparison, in terms of critical velocity, with experimental results available for public in the literature. Results which are based on CFD modeling show that the effect of obstacle blockage brings about a decrease of the critical velocity compared than to those obtained with an empty tunnel. This decrease depends on the obstacle location relative to tunnel floor. It is slightly greater when the distance between the bottom of obstacle and the tunnel floor increases. Further, when the obstacle exists in tunnel, the backlayering length become much smaller compared to those predicted in an empty tunnel.

1. Introduction

The road and the railway underground transport systems have undergone an important evolution to facilitate the passage of the mountainous regions and to preserve the environment in urban zones. Officials are faced not only with the question of the people and property security but also with public confidence in the tunnels as important means of transport. The fires which develop in these infrastructures have attracted a particular attention because of their disastrous consequences, such as the calamity of the Mont Blanc tunnel (39 deaths on March 24th, 1999) or the sinister criminal of the subway of Daegu Korea (198 deaths on February, 2003) (Mos, 2005). Smoke is the most mortal factor in fire case where a huge quantity of toxic gases is released as a result of an incomplete combustion (Hu et al., 2005).

Ventilation is a key element to guarantee a correct evacuation of users, contain the fire and control the dispersion of contaminants in tunnel (Tsai et al., 2010). The strategy of emergency planning and smoke control most currently used in majority of tunnels are based on the longitudinal ventilation produced mechanically (Kang, 2010). The minimum ventilation velocity, generally designated by the critical velocity, is simply the velocity by which all the smoke are pushed from one side. Below this velocity, a backlayering layer goes against the fresh air current produced by tunnel ventilation. One of the foremost criteria for the design of longitudinal ventilation system of tunnel is the critical velocity value (Tsai et al., 2011).

Currently, several different formulas to predict the critical velocity are obtained through a theory based on the Froude number preservation combined with some experimental data of small or full scale. Several authors agree that Thomas (1968) is one of the very first to be interested in the study and the determination of the critical velocity value. Thomas suggested that at the critical condition, the buoyancy and inertial forces are in balance. He proposes a Richardson number that is close to unity in critical situation. The Richardson number is defined by:

$$Ri = \frac{gH}{V^2} \cdot \frac{\Delta\rho}{\rho} = \frac{1}{Fr} \cdot \frac{\Delta\rho}{\rho} \tag{1}$$

A relationship between the critical velocity and the heat release rate of fire is then presented as follows:

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Nomenclature

A	cross sectional area of the tunnel, m^2
C_p	specific heat capacity, kJ kg^{-1} K^{-1}
C_s	Smagorinsky constant, –
D	diffusivity coefficient, m^2 s^{-1}
D^*	characteristic fire diameter, m
Fr	Froude number, –
g	gravitational acceleration, m s^{-2}
H	tunnel height, m
$\overline{H}$	hydraulic tunnel height, m
k_t	turbulent thermal conductivity, W m^{-1} K^{-1}
l^*	dimensionless backlayering length, –
L	backlayering length, m
$\Pr_t$	turbulent Prandtl number, –
Q	heat release rate from fire, kW
Q'	dimensionless heat release rate based on hydraulic tunnel height, –
Q^*	dimensionless heat release rate based on tunnel height, –
Q_{cv}	convective heat release rate, kW
Ri	Richardson number, –
Ri_{cr}	critical Richardson number, –
Sc_t	turbulent Schmidt number, –
S_{ij}	symmetric rate of strain tensor, s^{-1}

T	temperature, °C
T_0	ambient temperature, °C
$\boldsymbol{u}$	velocity vector, m s^{-1}
V	ventilation velocity, m s^{-1}
V^*	dimensionless confinement velocity, –
$V^*_{\max}$	constant, –
V_{cr}	critical ventilation velocity, m s^{-1}
V'_{cr}	dimensionless critical velocity based on hydraulic tunnel height, –
V^*_{cr}	dimensionless critical velocity based on tunnel height, –
W	tunnel width, m

Greek symbols

Δ	filter width in LES, m
$\Delta\rho$	density difference, kg m^{-3}
δt	time step, s
δx, δy, δz	grid size in coordinate directions (x, y, z), m
δx_i	grid size in direction i, m
μ_t	turbulent viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ρ_0	ambient density, kg m^{-3}

$$V_{cr} \approx \left(\frac{gHQ}{\rho_0 T_0 C_p A}\right)^{1/3} \tag{2}$$

Based on their small-scale experiments, Oka and Atkinson (1995) have inspired a "supercritical ventilation velocity" from which the critical velocity does not increase with the one-third power of the heat release rate. The experimental results can be expressed in a simple correlation in dimensionless form:

$$V^*_{cr} = V^*_{\max}(0.12)^{-1/3}(Q^*)^{1/3} \quad \text{for} \quad Q^* < 0.12 \tag{3}$$

$$V^*_{cr} = V^*_{\max} \quad \text{for} \quad Q^* > 0.12 \tag{4}$$

With V^*_{cr} and Q^* are the dimensionless critical ventilation velocity and the dimensionless heat release rate respectively. They are given by:

$$V^*_{cr} = \frac{V_{cr}}{\sqrt{gH}} \tag{5}$$

$$Q^* = \frac{Q}{\rho_0 C_p T_0 g^{1/2} H^{5/2}} \tag{6}$$

Wu and Bakar (2000) have identified, by experimental investigation and numerical simulation, a new model to predict the critical ventilation velocity for tunnels with various cross sectional geometry. The presented model confirms the model proposed by Oka and Atkinson (1995). This model shows clearly that there are two regimes of variation of critical velocity with heat release rate of the fire. Their suggested model is given as:

$$V'_{cr} = 0.40\left(\frac{Q'}{0.20}\right)^{1/3} \quad \text{for} \quad Q' \leqslant 0.20 \tag{7}$$

$$V'_{cr} = 0.40 \quad \text{for} \quad Q' > 0.20 \tag{8}$$

where V'_{cr} and Q' are the dimensionless critical ventilation velocity and the dimensionless heat release rate respectively. They are defined as follows:

$$V'_{cr} = \frac{V_{cr}}{\sqrt{g\overline{H}}} \tag{9}$$

$$Q' = \frac{Q}{\rho_0 C_p T_0 g^{1/2} \overline{H}^{5/2}} \tag{10}$$

With $\overline{H}$ is the hydraulic tunnel height.

Recently, Li et al. (2010) carried out experimental tests and theoretical analyses to study the critical velocity together with the backlayering length in tunnels fires. Based on their experimental tests, Li et al. (2010) propose:

$$V^*_{cr} = \begin{cases} 0.81Q^{*1/3} & \text{for} \quad Q^* \leqslant 0.15 \\ 0.43 & \text{for} \quad Q^* > 0.15 \end{cases} \tag{11}$$

Furthermore, Li et al. (2010) prove a relation between the ratio of longitudinal ventilation velocity to the critical velocity and the dimensionless backlayering length that follows an exponential relation. Yang et al. (2006) note an increase in the backlayering velocity and an expansion of its thickness and its length when the ventilation velocity decreases. A semi-empirical model is developed by Hu et al. (2008) to predict the backlayering length. From this model, they derive an equation to calculate the critical longitudinal ventilation velocity by placing the backlayering length equal to zero.

Lee and Tsai (2012) report that tunnel vehicles affect ventilation flow and tunnel fire behavior. Kang (2010) carries out a numerical modeling to examine the effect of enclosure blockage ratio on critical ventilation velocity. Blockage ratio is defined as the ratio of enclosure cross sectional area over tunnel cross sectional area. Three blockage ratios are considered: 25%, 50% and 65%. Kang (2010) reveals using hydraulic diameter as the characteristic length scale that the critical ventilation velocity decreases with the increase in blockage ratio. Li et al. (2010) have shown that the reduction rate of critical velocity due to the obstruction is slightly larger than the ratio of cross sectional area of vehicle to tunnel cross sectional area. In their studies, the model vehicle occupies about 20% of the tunnel cross section. Oka and Atkinson (1995) noted a decrease of around 15% and 40–45% in the critical velocity when the blockage ratio is 12% and 32% of the tunnel cross section, respectively. Lee and Tsai (2012) have investigated experimentally and by CFD analysis the influence of vehicular blockage on flow behavior of tunnel fires and on critical ventilation velocity by indicating that vehicles and fires are usually on the ground. However, it is significant to notice that really the bottom of vehicle has a certain distance to the tunnel floor which it depends on the