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A model for predicting smoke back-layering length in tunnel fires with the combination of longitudinal ventilation and point extraction ventilation in the roof

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ABSTRACT

An analytical model is developed for quantifying the fire smoke back-layering length in a tunnel with a combination of longitudinal ventilation and point extraction ventilation in the roof. The distance of smoke vent to fire source is incorporated as well as mass flow rate during the whole smoke flow process according to the mass conservation principle. The model input quantities are the heat release rate of the fire source, the longitudinal velocity, the exhaust velocity, the width and the height of the tunnel, the distance of the smoke vent to the fire source and the area of the smoke vent. The quality of the model predictions is illustrated for a range of experimental conditions. After that, extensive model predictions on the back-layering length are presented to show its trends by varying the velocity of the longitudinal ventilation, the exhaust velocity and the position of the smoke vent in the roof. Discussions are given at last. It is highlighted that shortening the distance between the smoke vent and the fire source benefits shortening the back-layering length, and this phenomenon is more pronounced for higher exhaust velocity.

1. Introduction

In the last few decades, tunnel fires have caused a lot of damage to properties and casualties (Hacck, 1998; Vuilleumier et al., 2002; Leitner, 2001), and the fire smoke is the leading reason. The danger of the smoke in tunnel fire not only results from the visibility obscuring effect but also from its toxicity. The ventilation systems are then applied in tunnels to deal with the fire smoke and the longitudinal ventilation system is a common one. The principle of the longitudinal ventilation is to blow the fire smoke to the downstream of the fire source so that the upstream side would be clear for evacuation and rescue. However, sometimes the longitudinal air flow would be smaller than the critical velocity due to the poor ventilation capability, large fire scale or the “throttling effect”. As a result, the smoke would spread upstream of the fire source and then the back-layering (upstream traveling of the smoke in the direction opposite to the ventilation) occurs. Apparently, the smoke back-layering would danger the evacuees and the rescuers upstream of the fire and lead to an increase in number of casualties in tunnel fires. So it is significant to study and quantify the back-layering length in the case of the tunnel fire.

Many scholars have developed models for quantifying the back-layering length, but most of them were developed in the contests of the tunnels with the longitudinal ventilations. Because of destroying the stratification of the smoke downstream of the fire source, the limitation in the use of the longitudinal ventilation system is apparent. The longitudinal ventilation is preferably applied to non-congested tunnels where there are normally no people downstream of the fire source. As for the urban tunnels designed for queues, it is a challenge to only adopt a sole longitudinal ventilation system. To take this challenge, the longitudinal ventilation is often designed together with the extraction ventilation in Chinese urban tunnels (e.g. Wuhan Yangtze River tunnel and Nanjing Yangtze River tunnel). When a fire occurs, the smoke vent closed to the fire source would open to assist in exhausting the fire smoke. It is no doubt that the point extraction ventilation in the roof would interact with the longitudinal ventilation system to affect the formation of the smoke back-layering. Present paper will focus on this phenomenon and build a model to quantify the length of the back-layering under the combined effect of the longitudinal ventilation and the point extraction ventilation in the roof.

The structure of this paper is as follows. A review of the models for

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Nomenclature

A	area of the smoke vent, m
A_t	cross-sectional area of the tunnel, m^2
B	tunnel width, m
C	coefficient constant
c_p	specific heat capacity, kJ/(kg K)
d	distance from smoke vent to fire source, m
D	contact length, m
$D^{'}$	characteristic length
Fr	Froude number
Fr_m	modified Froude number
g	gravitational acceleration, m/s^2
h	smoke layer height, m
H	tunnel height, m
H_d	height from fire source to tunnel ceiling, m
K	longitudinal decay coefficient of the ceiling excess temperature
$K^{'}$	modified longitudinal decay coefficient of the ceiling excess temperature
K_1	longitudinal decay coefficient of the ceiling excess temperature downstream the smoke vent
l	back-layering length, m
$l^{'}$	the second part of back-layering length,
l^{*}	dimensionless back-layering length
l^{**}	modified dimensionless back-layering length
$\dot{m}$	plume mass flow rate, kg s
$\dot{Q}_c$	convective heat release rate, kW
$\dot{Q}$	heat release rate, kW
$\dot{Q}^{*}$	dimensionless heat release rate
$\dot{Q}^{**}$	modified dimensionless heat release rate
r	radius of the fire source, m
$Ri^{'}$	modified Richardson number
T	temperature, K
V	velocity, m/s
V^{*}	dimensionless longitudinal velocity
V^{**}	modified dimensionless longitudinal velocity
$V^{'}$	longitudinal velocity induced by both the longitudinal ventilation and the point extraction, m/s
V_a	longitudinal velocity induced by the longitudinal ventilation, m/s
V_c	critical velocity, m/s
w^{*}	characteristic plume velocity, m/s
x	coordinate at the virtual x-axis, m
x_0	coordinate of the position of the maximum excess ceiling temperature, m

Greek symbols

α	heat transfer coefficient
γ	experiments coefficient
ε	experiments coefficient
ρ	density, kg/m^3
θ	flame angle, °
Δ	excess over the initial value
δ	proportional coefficient

Subscript

0	initial value
a	ambient
ex	exhaust
in	induced
max	max value
r	residual
s	stagnation
up	upstream

quantifying smoke back-layering flow length is presented firstly. Then, the phenomenon described by the model is introduced before the introduction of the phenomenon described by the model. Next, the accuracy of the model for predicting the back-layering length is illustrated by means of the experimental data and a third party model. Afterwards, the influences of the longitudinal velocity, the exhaust velocity and the distance of the smoke vent from the fire source on the back-layering length are discussed, and some conclusions are made at last.

2. Literature review

In the previous research, many models (Chow et al., 2015; Vantelon et al., 1991; Li et al., 2010; Deberteix et al., 2001; Thomas, 1958) have been developed to predict the length of back-layering. However, most of them are aim to serve for the purely longitudinal ventilated tunnels, and a few studies consider the contexts of the combination of the longitudinal ventilation and the point extraction ventilation in the roof.

In 1958, a theory of describing the back-layering length was proposed by Thomas (1958) in 1958. In Thomas (1958); the dimensionless back-layering length; l^{*}, was correlated with a modified Froude number, $Fr_m = \frac{gH\Delta T}{V_a^{2}(T_a+\Delta T)}$. The proposed relation was expressed as follows:

$$l^{*} = \frac{l}{H} \propto \frac{gFr_m}{\rho_a c_p V_a \Delta T A_t} \tag{1}$$

where g is the gravitational acceleration, H is the tunnel height, ρ_a is the ambient air density, c_p is the specific heat capacity of air, l is the back-layering length, V_a is the longitudinal velocity, A_t is the cross-sectional area of the tunnel, T_a is the ambient temperature. ΔT is the temperature excess over ambient.

In 1991, Vantelon et al. (1991) defined a modified Richardson number, $Ri^{'} = \frac{g\dot{Q}_0}{\rho_a T_a c_p V_a^{3} H}$, and proposed that the dimensionless back-layering length varied as 0.3 power of $Ri^{'}$, given as:

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

where $\dot{Q}_0$ is the heat release rate of the fire source.

In 2001, based on the experiments performed in a model tunnel of Paris metro, Deberteix et al. (2001) correlated the back-layering length with the Richardson number; $Ri = \frac{gD^{'}\Delta T}{V_a^{2} T_a}$, to proposed the equation as follows:

$$l^{*} = 7.5(Ri^{1/3}-1) \tag{3}$$

where $D^{'}$ is a characteristic length.

In 2010, Li et al. (2010) performed small-scale experiments and correlated the dimensionless smoke back-layering length to the dimensionless heat release rate of the fire source and the dimensionless longitudinal velocity. The correlation shows as follows:

$$l^{*} = \begin{cases} 18.5ln(0.81\dot{Q}^{*1/3}/V^{*}), \ \dot{Q}^{*} \le 0.15 \\ 18.5ln(0.43/V^{*}), \ \dot{Q}^{*} > 0.15 \end{cases} \tag{4}$$

where

$$l^{*} = \frac{l}{H} \tag{5}$$

$$V^{*} = \frac{V_a}{\sqrt{gH}} \tag{6}$$