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Theoretical analysis on plane fire plume in a longitudinally ventilated tunnel

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ABSTRACT

This paper presents a theoretical analysis on the longitudinal tunnel ventilation in fire emergency based on a plane fire plume model. The objective of the current research is to understand the physical mechanism leading to the decoupling of critical velocity and HRR in the case of large tunnel fire. The solution of the analysis has established a critical *Fr* curve that changes continuously from what can be approximated by Thomas' cubic root correlation to a constant limited by Archimedes' principle. The turning point between the two ventilation regimes is the unit relative tunnel height to the height of flame. The current analysis has revealed that in order to predict the behaviour of critical velocity correctly, all three controlling factors, namely fire, ventilation and tunnel height must be taken into account. Both traditional ceiling plume theory and Thomas' correlation are inadequate in analysing tunnel fire ventilation. The former does not include forced ventilation and the later has left tunnel height out. The current *Fr* curve has provided the theoretical maximum critical velocity that can serve as guidance for fan sizing in tunnel ventilation design. Comparison between the prediction from the current theory and three independent sets of experimental data has shown excellent agreement.

1. Introduction

The critical velocity in tunnel emergency ventilation is hardly a fresh topic. After more than 40 years and countless research papers published, there is still a compelling issue left: the physical mechanism. It is the drive behind the current paper.

The interest of finding critical ventilation velocity started from Thomas in 1968 (Thomas, 1968). He suggested that critical ventilation velocity should be determined by the balance between the buoyancy force from combustion and the inertial force of ventilation. The following correlation was given based on his scale analysis.

$$u_v^3 = k\frac{gq_f}{c_p\rho_v T_v} \tag{1}$$

where q_f is the heat release rate of fire per unit tunnel width. The above expression is often referred as Thomas' cubic root correlation. Subsequent experiments have shown that this correlation is quite adequate for small to medium size fire (Hinckley, 1970; Heselden, 1976; Danziger and Kennedy, 1982; Vantelon et al., 1991; Oka and Atkinson, 1995; Wu and Bakar, 2000; Li et al., 2010; Lee et al., 1979; Grant et al., 1998). In large fire, Oka has shown that correlation (1) failed to predict the "leveling-off" of critical velocity when the heat release rate of fire exceeds 10 kW in his experiment. A two-part correlation was recommended by Oka to represent his experimental data (Oka and Atkinson, 1995). No attempt had been made to explain why the critical velocity was decoupled from fire size when the later was increased over certain size.

Recently, Kunsch (2002) presented a model analysis based on the semi-empirical theory of circular plume. The model yields a formula for estimating the critical velocity. It shows the asymptotic behaviour on both the small and large fire ends consistent with experimental founding from Oka.

The first question raised from Kunsch's analysis is the physical model adopted in developing his expression for critical velocity. The model started from vertical temperature and velocity distributions that are for circular ceiling plume without any cross ventilation. How does the air entrainment in the model compare with the forced ventilation at near critical condition in tunnel? There is no justification from the author about this point. Secondly, neglecting plume deflection due to ventilation may be acceptable for studying backlayering. However under critical ventilation condition, half of the ceiling jet has disappeared. Obviously there would be no axisymmetric fire plume as assumed by the author. Although the output of the model seems fit the experimental data presented, the author has not offered much of physical explanation of it.

In experimental research, small-scale investigations are attractive because they allow more control over the experimental conditions and are generally more economical to perform parametric study. Their use depends on the accuracy of the scaling model employed. Care is required in the design of the experiment to ensure

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Nomenclature

c_p	specific heat at constant pressure (J/kg K)
Fr	*Froude* number
g	gravity (m/s^2)
h	specific enthalpy (J/kg)
H	tunnel height (m)
k	Thomas' constant.
L	flame height (m)
m	mass flow rate (kg/s)
p	pressure (N/m^2)
Q	total thermal power (W)
q	heat release rate of fire per tunnel width (W/m)
T	local temperature in fire plume (K)
u	local velocity (m/s)
w	tunnel width (m)
x	longitudinal coordinate (m)
z	vertical coordinate (m)
Δz	thickness of backlayer (m)

Greek

δ	longitudinal width of fire plume (m)
ρ	density (kg/m^3)

Superscript/Subscript

$'$	dimensionless quantity.
$*$	dimensionless quantity as defined by Oka.
0	state at the beginning of backlayer.
f	flame property
s	stagnation state
t	gas state at the interface between smoke layer and the main body of fire plume.
v	property of ventilation air.
x	x-component of a vector
z	z-component of a vector

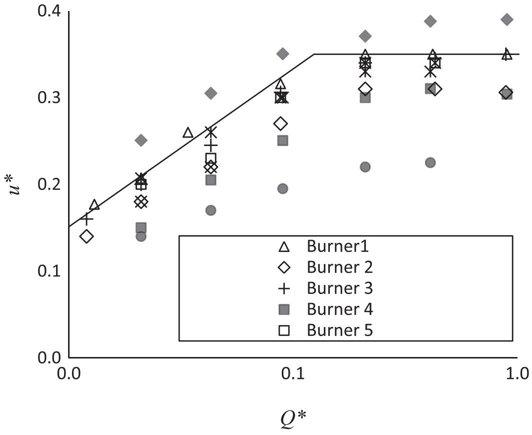

Fig. 1. Experimental data and correlation from Oka and Atkinson (Oka and Atkinson, 1995).

that the most important processes are scaled correctly and that dynamic similarity is retained (Grant et al., 1998). In correlating experimental data, there are *Froude* modelling (e.g. Thomas, 1968; Danziger and Kennedy, 1982; Oka and Atkinson, 1995; Wu and Bakar, 2000) and *Richardson* modelling (Vantelon et al., 1991). In the *Froude* modelling campus, there is also the argument of what length scale should be used in forming *Froude number* (Oka and Atkinson, 1995; Wu and Bakar, 2000). In the widely quoted correlations from Oka and Atkinson (1995) and Wu and Bakar (2000), tunnel height/diameter has been used to normalise both critical velocity and heat release rate. In the case of heat release rate, the weighting of tunnel height is to the power of 5/2. Question has to be asked whether too much weight is given to a single parameter. If so, some other influential factors may be missing there.

The correlations from Oka and Atkinson (1995) and Wu and Bakar (2000) contain two distinctive expressions of critical velocity for different fire size ranges. It implies two different physical mechanisms at work. What are they and what controls the system switching from one regime to another? No one has offered adequate answer.

Beside the above questions, the systematic discrepancy of experimental data in the same order as the value itself (Fig. 1) deserves explanation in order to tell the tunnel designers how the data can be used in practice and what error range should be expected.

Tunnel ventilation system designers are required to ensure the safety of tunnel users in any anticipated fire event but also need to keep the cost of the system to what is really necessary. Finding the true mechanism of tunnel emergency ventilation and accurately quantifying the maxima of ventilation velocity against fire size in a given tunnel environment is crucial for fan sizing therefore have important safety and cost implication. The inadequacy in Thomas' correlation and the uncertainty among various other experiment based correlations have raised the issue of more fundamental research and better understanding on how the ventilation flow interacts with fire in tunnel environment.

2. The fire plume model in the current study

2.1. The physical model

In the current study, a pool fire is modelled as a plane buoyant plume rising from tunnel surface toward the ceiling as shown in Fig. 2. The fire pool is a transversal trench dug across the tunnel floor. Fuel surface is at $z = 0$ and the total heat release rate of the fire is assumed to be Q_f. Instantaneous combustion takes place at the surface of the pool. Above it, there is no further chemical reaction. Both the ventilation air and the combustion product are treated as ideal gas and laminar viscosity of fluid is omitted. Considering both tunnel ventilation on the front side (left) and the buoyancy force on the back side (right) of the fire plume, air entrainment due to turbulent mixing has been ignored, therefore the only air supply to the fire plume is from tunnel ventilation. Considering the decrease of temperature and the increase of mass flux along the trajectory of the fire plume, its width δ has been taken as a constant up to the ceiling layer in the current model. The tunnel is assumed to be so wide that no influence of the side wall needs to be accounted for.

2.2. The mathematic model

In this study, only the flow in steady state is considered. Based on the assumptions in the last section, the general equations governing the average mass, momentum and energy balance of the fire plume in z-direction can be written as (Fig. 2):

$$\frac{d(m)}{dz} = \rho_v u_v w \tag{2}$$