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Analytical solution, experimental data and CFD simulation for longitudinal tunnel fire ventilation

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ABSTRACT

A new integral theory for tunnel fire under longitudinal ventilation has been presented. Its solution on critical velocity has been compared with experimental data and the results of CFD simulation from two different computer programs. The exercise of cross examination is not only aimed at further verification of the new theory but also to reveal any problem in all three kinds of data being compared, particularly the pitfalls that may exist in CFD simulation. The comparison has shown that the general agreement among all three kinds of data is satisfactory. Both theoretical and CFD predictions have confirmed the trend of variation for critical velocity versus fire size shown in the experimental data. However the CFD prediction from FDS program for a narrow tunnel has failed to conform to the same trend as that in the theory and experimental data. Considering similar FDS result in comparable condition previously published by another researcher, the authors of the current article believe that CFD simulation results for tunnel fire need to be more closely scrutinized. The simulated result may not only contain numerical error but also go way out of trend and difficult to be physically interpreted. Discrepancy between the current theory and experimental data in some cases is believed due to flame heat loss that has not been accurately predicted by the theory.

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1. Introduction

1.1. Fire risk in a traffic tunnel

It is a common knowledge that fires in tunnel can lead to catastrophic consequence. Dangerous cargo such as petrol or diesel fuel can cause fire up to few hundred MW. Very limited space may have to be shared by the tunnel users and fire smoke. Long walk towards the ground exit accompanied by the possibility of inhaling toxic and high temperature smoke reduces people's survivability. The principle life saving measures are extinction, dilution and compartmentation. Rapid extinction and dilution, as self rescue measures, are only possible when the fire is small. For large fire, such as that resulting from HGV or fuel tank, compartmentation would be the most effective protection. In a traffic tunnel, compartmentation could be achievable with the assistance of longitudinal ventilation. If the traffic in tunnel is unidirectional, ventilation in the traffic direction could limit it to the downstream of the fire site. It leaves the upstream clear from smoke for evacuation and fire fighting. In a bidirectional traffic tunnel, longitudinal ventilation is used to limit the extend of smoke infected section and support thermal stratification while smoke extraction is in operation.

Since most traffic tunnels are part of a strategic transport network, structural protection should follow the life saving operation. Prolonged interruption of traffic has very significant social, economical and political implication. In large tunnel fire, direct structural damage would appear around the area suffering the highest thermal load. As smoke temperature is related to buoyancy force, the highest smoke temperature should be found on the ceiling of tunnel where the flame has touched. Although ventilation can be used to lower the maximum smoke temperature through dilution, the same ventilation air also provides extra oxygen to the fire therefore may intensify it and result in even higher thermal load to tunnel ceiling. How to strike the balance is still a problem having no general answer (Carvel, 2004).

In recent years, the concept of fire suppression has been introduced into tunnel fire protection. One of its most obvious advantages is reducing structural thermal load. There are large scale experiments being carried out. Its effectiveness, balance of benefit and cost as well as its drawbacks are still waiting to be clarified (Carvel, 2012).

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Nomenclature

A	tunnel cross section area
Fr	Froude number
g	gravity (m/s^2)
h	specific enthalpy (J/kg)
H	tunnel height (m)
k	constant
L	Flame height (m)
m	mass flow of smoke (kg/s)
Q	heat release rate of fire (W)
T	local temperature in fire plume (K)
u	local velocity (m/s)
w	tunnel width (m)
z	vertical coordinate (m)

Greek

δ	longitudinal dimension of fire pool (m)
ρ	density of smoke (kg/m^3)

Superscript/Subscript

$'$	dimensionless quantity
f	property of fuel
v	property of ventilation air
x	x-component of a vector
z	z-component of a vector

1.2. What makes a tunnel fire special?

As mentioned above, whenever a fire occurs in a traffic tunnel, longitudinal ventilation is likely to present. It makes a tunnel fire distinctively different from what can be called a compartment fire. The theory of compartment fire is based on a model of axisymmetric diffusion flame beneath an unconfined ceiling (Fig. 1). Air supply to the fire relies on buoyancy driven entrainment (SFPE, 2008). The air entrainment and therefore smoke generation rate depend on the heat release rate (HRR) of fire. Ceiling temperature rise and the velocity of ceiling jet are determined by the HRR of fire and the height of ceiling (McCaffrey and Cox, 1982).

In a tunnel fire, ventilation is independent of the fire itself. In order to achieve compartmentation, the ventilation velocity needs to exceed the critical velocity. Under such condition, entrainment (in the traditional sense) does not control the air supply to fire and the fire plume cannot be treated as axisymmetric. Fig. 2 shows the photos taken during Gulf Mexico oil spill in 2010 (http://www.gulfoilspill.com, 2012). The same fire had presented very different characteristics in different air conditions. On the left, the fire was clearly developing in quiescent air and showing smoke rising from typical axisymmetric diffusion flame. On the right, the fire plume had been deflected by strong surface wind. It should be the kind of fire expected in a longitudinally ventilated tunnel. Describing it using the traditional diffusion flame theory would be a misrepresentation of the underline physics. Although applying compartment fire model in tunnel fire ventilation is currently common among tunnel fire researchers (Kunsch, 2002; Oka and Atkinson, 1995; Wu and Bakar, 2000), its fidelity should be called in question.

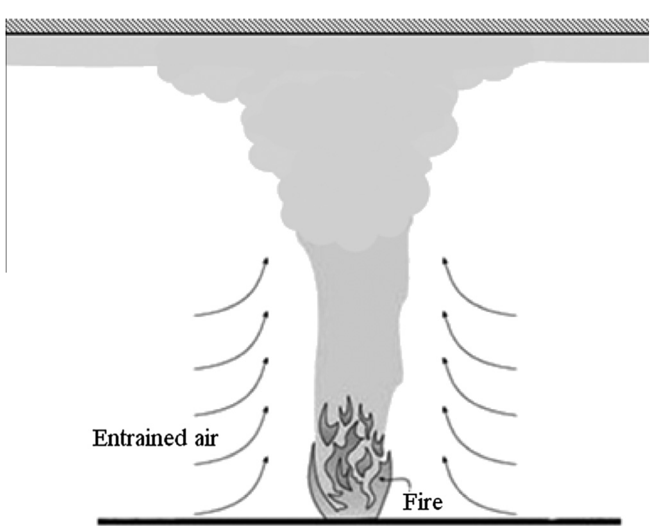

Fig. 1. The compartment fire model.

1.3. Why is the cubic root theory not for large fire?

Suitable fire models for tunnel like structures were initially sought after in mining as well as building fire research (Chaiken et al., 1979; Hwang et al., 1976; Thomas, 1958, 1968). Regarding critical ventilation velocity, the most influential result is the cubic root theory from Thomas et al. (1968). In tunnel fire community, it has become the rule of thumb regardless its failure in predicting the weak dependency of critical velocity on heat release rate of large tunnel fires. Its later version from Danziger and Kennedy (1982) has been included in the recommendations of PIARC (2005) and NFPA (2008).

Fig. 3 is the original drawing from Thomas showing his physical model for developing the cubic root theory (Thomas, 1968) where P is the location of fire. X and a mark the upstream and downstream of the fire site respectively. The model is one dimensional and horizontal. Thomas had used it to represent small corridor fire in a building without thermal stratification. Although Thomas had applied Froude scaling, his momentum balance was horizontally along the corridor. If the buoyancy proposed in the model by Thomas is replaced by thermal expansion, the same conclusion can also be reached. It demonstrates that the cubic root theory is not necessarily buoyancy related. That is why it has failed in predicting the critical velocity in large tunnel fires (Oka and Atkinson, 1995) that are dominated by buoyancy generated stratification in the vertical direction.

2. A model of longitudinally ventilated tunnel fire

2.1. Why do we still need analytical solution?

Since the end of last century, computational fluid dynamics (CFD) simulation has become more and more involved in the quantitative analysis of tunnel fire risk. It solves the basic set of partial differential equations (PDEs) numerically with minimum physical modeling requirement from the user. It can simulate an almost exact fire scenario with a few mouse clicks and produces visually realistic output. Its attraction is irresistible to fire safety designers, tunnel owners and also the regulators. As the user interfaces of the modern commercial packages have simplified the simulation task

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