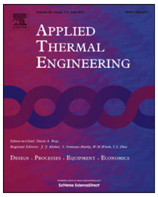
Applied Thermal Engineering 59 (2013) 101–105

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Measuring fire size in tunnels

Xiaoping Guo [a], Qihui Zhang [b,*]

[a] School of Energy and Power Engineering, Dalian University of Technology, 116023 Dalian, China
[b] GEODATA Engineering, Via Civinini 69, 00197 Rome, Italy

HIGHLIGHTS

- Fire sizing is an important safety measure in tunnel design.
- New measure of fire size a function of HRR of fire, tunnel height and ventilation.
- The measure can identify large and small fires.
- The characteristics of different fire are consistent with observation in real fires.

ARTICLE INFO

Article history:
Received 19 January 2013
Accepted 1 May 2013
Available online 20 May 2013

Keywords:
Tunnel fire
Ventilation
Fire size
Fire safety

ABSTRACT

A new measure of fire size Q' has been introduced in longitudinally ventilated tunnel as the ratio of flame height to the height of tunnel. The analysis in this article has shown that Q' controls both the critical velocity and the maximum ceiling temperature in the tunnel. Before the fire flame reaches tunnel ceiling ($Q' < 1.0$), Froude number Fr increases with Q', which is the typical trend of small tunnel fire. Once the flame height exceeds the height of tunnel ($Q' > 1.0$), Fr approaches a constant value. This is also a well-known phenomenon in large tunnel fires. Tunnel ceiling temperature shows the opposite trend. Before the fire flame reaches the ceiling, it increases very slowly with the fire size. Once the flame has hit the ceiling of tunnel, temperature rises rapidly with Q'. The good agreement between the current prediction and three different sets of experimental data has demonstrated that the theory has correctly modelled the relation among the heat release rate of fire, ventilation flow and the height of tunnel. From design point of view, the theoretical maximum of critical velocity for a given tunnel can help to prevent oversized ventilation system.

1. Introduction

A fire in a traffic tunnel can lead to two kinds of loss: the loss of human life and the damage to tunnel infrastructure. When fire occurs, the protection of human life has the priority over that of infrastructure. However the later should not be ignored. In 1999, the fire of Mont Blanc tunnel cost 39 lives, lasted 53 h and the tunnel was closed for three years following the fire. The true economical cost may never be known. At design stage, both kinds of risk should be properly assessed.

With a given design fire scenario, how a tunnel designer can assess the fire risk and predict the possible consequence within the residual risk even the unthinkable occurs? At the moment, the judgement is solely based on the peak heat release rate of fire. Numerous experiments have been carried out since the end of last century. Ingason has given a summary of such data and categorised the possible scenarios and consequences [1]. Table 1 illustrates Ingason's conclusion. Based on Table 1, any tunnel fire with heat release rate larger than 5 MW can be regarded as a life threatening event. If it is larger than 50 MW, the tunnel structure would be in danger. The peak size of any fire with heat release rate less than 200 MW will be independent of oxygen supply. In other words, the fire can reach the given heat release rate without additional air supply mechanism such as mechanical ventilation. On this point, the data in Table 1 is consistent with what shown in the SFPE Handbook [2].

Although Ingason has provided a general guide in the determination of design fire and its possible consequence, intuition tells us that the same fire can lead to very different result in different tunnel and ventilation configuration. More quantitative risk assessment requires better understanding on the physical mechanism of fire development within a tunnel ventilation environment. In the current article, a more comprehensive measure of fire size is presented based on a new theory of tunnel fire ventilation which

---

* Corresponding author. Tel.: +39 0115810699.
E-mail addresses: qzh@geodata.it, zxcomputing@hotmail.com (Q. Zhang).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.05.009

Table 1
Possible tunnel fire examples.

		Road vehicles examples	Rail vehicles examples	Metro vehicles examples
Risk to life		HRR < 30MW		
	Risk to construction	50MW < HRR < 70 MW		
		HRR > 100MW		

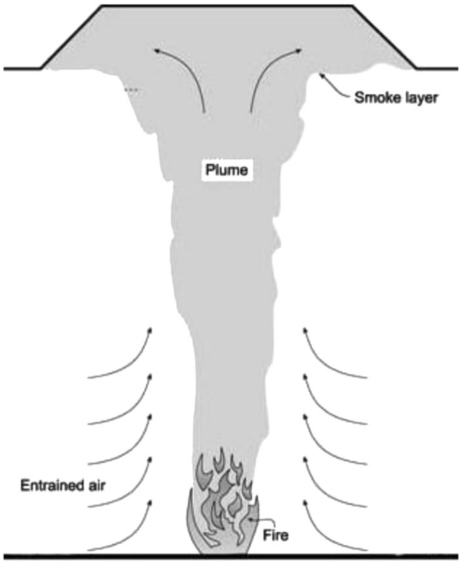


Fig. 1. Compartment fire model.

has revealed the logical relation among the heat release rate of fire, ventilation flow and tunnel cross section.

The new theory is different in two aspects from existing theories in tunnel fire safety, namely the thermal stratification and air supply to fire flame. The existing correlations for critical velocity (e.g. Refs. [3–5]) are all based on Thomas' cubic root theory. In his original paper, Thomas studied a fire scenario in building corridor that exhibits an almost uniform smoke front towards the ventilation flow (Fig. 3). No thermal stratification has ever been mentioned there [6], which was a valid description of the far field of a reasonably small corridor fire. However, with large fire a smoke layer would be formed under the ceiling of tunnel. The temperature within the smoke layer could be several hundred degrees higher than that of the air underneath it. It is the reason why all cubic root correlations failed in predicting the critical velocity in large tunnel fires.

As for the air supply to fire flame, existing correlations such as that given by Oka [4] and Wu [5] have incorporated the model of compartment fire. It implicates that the transversal velocity (entrainment velocity) should be proportional to the square root of vertical distance from the fire source [7]. Such an assumption directly contradicts the boundary condition in tunnel fire ventilation that the ventilation air velocity is given therefore independent of either tunnel geometry or the fire itself.

The new theory has addressed the above problems by using the ventilation velocity for the air supply to fire and set the critical condition as the momentum balance between the backlayering smoke and the ventilation air only within the smoke layer instead of entire tunnel cross section. It has led to the critical velocity limited by the limitation of total buoyancy in the fire flame due to the restrain of tunnel height.

Some of the more recent articles in tunnel fire research concern the effect of vehicular blockages on tunnel fire [8,9]. However, the current paper concentrates on understanding the basic flame behaviour of simple pool fire.

2. Tunnel fire

An essential component of a modern tunnel fire protection system is longitudinal ventilation. In order to effectively control fire smoke, the ventilation velocity should be at or above the local critical velocity. It means that a tunnel fire is almost always under the influence of strong cross air flow. This kind of fire should be distinguished from what is called compartment fire that is self-sustained via air entrainment as shown in Fig. 1. The distinction can be easily recognised by comparing the fires shown in Fig. 2.

On the left of Fig. 2, the air surrounding the fire is in a quiescent state. The fire plume is produced by the traditional axisymmetric diffusion flame as in the compartment fire model. The diameter of the plume column increases with height. In contrast, the fire plume on the right has been deflected by strong wind and the diameter of the plume is almost constant. It is the kind of fire that can be expected in a longitudinally ventilated tunnel. When such fire is moved into a tunnel, the plume column will be shortened and a smoke layer will be formed under the ceiling of tunnel [10].

3. The new model of tunnel fire ventilation

To understand the interaction between tunnel ventilation and fire, Thomas [6] had proposed a model as shown in Fig. 3. It is a one-dimensional model in the horizontal direction. In this model Thomas applied Froude scaling and reached the conclusion that the critical ventilation velocity in a longitudinally ventilated tunnel is proportional to the cubic root of the heat release rate of fire. This model has later been extended to tunnels with gradient by Danziger [3]. Their extension has now been included into the recommendations from both NFPA [11] and PIARC [12].

In 1990s, based on the data from full scale experiments, researchers in the Health & Safety Laboratory, UK realised that the critical velocity in large tunnel fires became weakly dependent on the heat release rate of fire, not as described by Thomas' cubic root theory [13]. Oka therefore made the suggestion of using a two-part formula calculating the critical velocity. The first part, for small fires only, was still in a cubic root form similar to that from Thomas but the effect of tunnel height had been accounted with compartment fire model. The second part that is for large fire is in the form of a constant Froude number [4].

The formulae for predicting the critical velocity of tunnel fire ventilation, although still popular in tunnel fire protection community, failed to explain the real physical process of tunnel fire. Thomas' model as shown in Fig. 3 is in fact a model of one-dimensional thermal expansion. The introduction of buoyancy in the form of Froude number in such a model was rather arbitrary and not explained by Thomas or any one following him. As a matter of fact, a substitution of buoyancy by pressure in the model could