International Journal of Thermal Sciences 132 (2018) 285–295

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Study on the smoke stratification length under longitudinal ventilation in tunnel fires

Zhen Zeng[a,b], Kang Xiong[a], Xin-Ling Lu[a], Miao-Cheng Weng[a,c,d,*], Fang Liu[a,c,d]

[a] Key Laboratory of Three Gorges Reservoir Region's Eco-Environment, Chongqing University, Chongqing, 400045, PR China
[b] China Railway Eryuan Engineering Group Co. Ltd, Chengdu, 610031, PR China
[c] National Centre for International Research of Low-carbon and Green Buildings, Chongqing, 400045, PR China
[d] Joint International Research Laboratory of Green Building and Built Environment, Ministry of Education, Chongqing, 400045, PR China

ARTICLE INFO

Keywords:
Interval tunnel
FDS numerical simulation
Small-scale experiment
Smoke stratification length

ABSTRACT

Smoke temperature distribution and smoke stratification law in the interval tunnel were studied through a series of experiments conducted in a 1/15 scale model tunnel. The small-scale experiment proved that the dimensionless temperature ratio method proposed by Newman was feasible. Based on the FDS simulation, smoke stratification under different longitudinal ventilation was studied, and the concept of smoke stable-stratification-length was presented. The influence of the heat release rate and the tunnel section on the smoke stable-stratification-length was analyzed. Thereafter, prediction models for the smoke stable-stratification-length and the critical stratification velocity were proposed. It can provide a reference for the design of longitudinal ventilation and smoke exhaust system of tunnels.

1. Introduction

Statistics show that the most of the casualties in metro tunnel fire are caused by breathing too much toxic smoke, which may lead to death due to lack of oxygen [1]. When a fire occurs in a tunnel, the smoke may gather in the upper part of the tunnel and form a layer of smoke through thermal buoyancy. At the beginning of the fire, maintaining a stable thermal stratification can make smoke gather in the upper space of the tunnel, which can help in evacuation and escape of people.

Tunnel ventilation system is mainly used to improve the environment in the tunnel and control the smoke and reduce the harmful effects to people. In the event of fire, longitudinal ventilation system must be able to reach the longitudinal critical velocity which does not produce reflux smoke to meet the needs of upstream personal evacuation. At the same time, in order to create a good fire conditions when firefighters come into the tunnel, it requires that the thermal stratification of downstream smoke is intact, which can be exhausted from the side of the tunnel or at the top of the tunnel. When longitudinal ventilation system is adopted, the longitudinal flow air of the tunnel and the smoke layer produce shear so that the downstream smoke layer is unstable and destroys the layered structure.

Lemaire and Kenyon [2,3] carried out fire experiment in Benelux tunnel group on the effects of longitudinal ventilation on the early stage of tunnel fire, including the law of smoke stratification or mixed variation, the front velocity of smoke and the critical velocity. They also carried out research on the effects of forced ventilation on HRR and tunnel environment, and the effects of fire suppression efficiency, steam volume, system delay action of automatic sprinkler system on tunnel fire control. They confirmed the previous conclusion that 3 m/s critical velocity was enough to prevent the back flow of smoke and the car fire. The longitudinal ventilation could destroy the thermal layer of the smoke in the downstream, and the visibility of the downstream is obviously reduced.

Newman's study [4] showed that the flow of hot smoke and cold air was stratified in the tunnel, and forced longitudinal ventilation may cause sufficient mixing of the upper smoke with the lower cold air in the tunnel.

A study on tunnel fire experiment by L.H.Hu et al. [5] found that the longitudinal ventilation would lead to significant increase in the thickness of the smoke layer. Q.K. Xu [6] conducted a study on fire smoke movement in a narrow tunnel, and studied the rule of influence of heat release rate of fire source and longitudinal ventilation on the stability of smoke thermal stratification by using small scale narrow tunnel experiments. Some basic concepts such as stratification intensity and stratification curve were defined. Some laws of thermal stratification in quasi steady state zone were studied. At the same time, the pulsation and migration characteristics of fire smoke in the narrow tunnel were studied by theoretical analysis and numerical experiments.

* Corresponding author. Chongqing University, Shapingba District, 400045, PR China.
E-mail address: mcweng@outlook.com (M.-C. Weng).

https://doi.org/10.1016/j.ijthermalsci.2018.05.038
Received 9 December 2017; Received in revised form 14 May 2018; Accepted 24 May 2018
1290-0729/

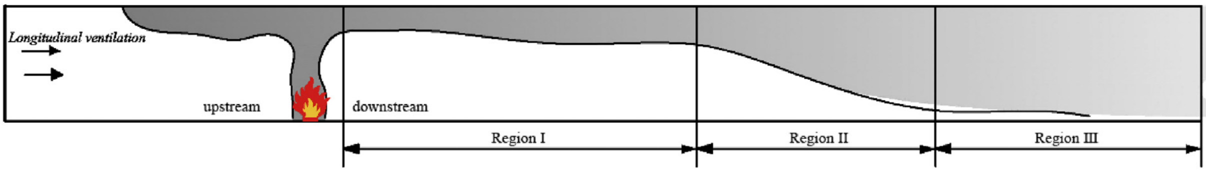

Fig. 1. Smoke stratification.

A large number of simulations and experiments have been carried out by some scholars in the past on smoke flow and smoke control in tunnel fires under longitudinal ventilation [7–9]. Based on different longitudinal ventilation and smoke exhaust rates in the road tunnel, researchers have carried out studies on the distribution characteristics of smoke temperature and the height of the smoke layer [5]. The results showed that longitudinal ventilation has a great influence on the smoke stratification. M.C. Weng [10,11] carried out research on the back-layering length and critical velocity of the longitudinal ventilation in the tunnel. However, relevant research on the smoke stratification of the metro tunnel is somewhat limited. The study of critical velocity is necessary to ensure that there is no smoke in the upstream direction when longitudinal ventilation is provided in metro tunnel, and the study on the thermal stratification of the smoke is to ensure the stable stratification and the smoke control in the downstream direction. The relationship between the thermal stratification of the smoke and the critical velocity is also worth exploring. Therefore, the study on the temperature distribution of smoke and the phenomenon of smoke stratification under longitudinal ventilation can provide theoretical guidance for smoke detection, smoke control and effective management in the early stage of fire in metro tunnel.

In order to study the smoke thermal stratification in metro tunnel, small-scale experiments and FDS simulations were carried out in this paper. The influence of different heat release rates and longitudinal ventilation rates on thermal stratification of quasi steady state in the downstream direction were considered. A new concept of smoke stable-stratification-length has been proposed, which is an index reflecting the stability of smoke stratification along the longitudinal direction of the tunnel. And a prediction model of smoke stratification length was obtained. Then, the relationship between the critical velocity and the critical stratification velocity was discussed. The research provided some references for the design of longitudinal ventilation and smoke exhaust system of tunnels.

2. Theoretical analysis

2.1. Research on the smoke stratification

Newman [4] proposed that under the influence of longitudinal wind shear in tunnel fires, smoke layer can be divided into three regions (Fig. 1): stable buoyant stratification (Region I), stable buoyant flow stratification but with interfacial instability (Region II), and unstable stratification (Region III) [4,12–14]. At present, there are two ways to divide the smoke stratification. The first method is determined by calculating the height of the smoke layer [15,16]. The second method is determined by the critical parameters, such as $\Delta T_{cf}/\Delta T_{avg}$, Froude number or Richardson number [4,12]. Where $\Delta T_{cf}/\Delta T_{avg}$ is a dimensionless temperature ratio, which reflects the intensity of the thermal stratification of smoke.

There are many ways to calculate the height of the smoke layer, such as N-percentage method, maximum gradient method, integral ratio method, minimum flat method and so on, but none of them is perfect. Both N-percentage method and maximum gradient method are semi-empirical formulas. As for the integral ratio method and least squares method, there would be obvious errors in the calculation under the circumstance that the change of parameters of the entire longitudinal region is superficial and without obvious stratification.

Many predecessors have studied the behavioral characteristics of smoke stratification by studying the parameters at the regional boundaries:

Newman [4] carried out a study on tunnel fire experiments under different fuels, heat release rates and velocities in a large tunnel (2.4 m × 2.4 m × 46.7 m). By analyzing the ceiling temperature, the floor temperature and the average temperature of the tunnel section, Newman first proposed the dimensionless temperature ratio as the criterion of the smoke partition, that is, the criterion of $\Delta T_{cf}/\Delta T_{avg} = 1.7$ (Region I: $\Delta T_{cf}/\Delta T_{avg} > 1.7$ (with clear stratification), Region II: $\Delta T_{cf}/\Delta T_{avg} \leq 1.7$ (with less clear stratification)), Where $\Delta T_{cf}/\Delta T_{avg}$ is a dimensionless temperature ratio, which reflects the intensity of the thermal stratification of smoke. Newman plotted the results of two dimensionless temperature ratios on a logarithmic graph, as shown in Fig. 2. The abscissa is $\Delta T_{cf}/\Delta T_{avg}$ and the ordinate is $\Delta T_{cf}/\Delta T_h$. When $\Delta T_{cf}/\Delta T_{avg} > 1.7$, the data point is located on the right side of the dotted line. At this time $\Delta T_{cf}/\Delta T_h \approx 1$, the tunnel surface temperature is almost the same as the ambient temperature, and the smoke is not exposed to the ground. Smoke stratification is stable, then the location of the smoke stratification is in Region I. When $\Delta T_{cf}/\Delta T_{avg} \leq 1.7$, the data point is located on the left of the dotted line, at this time $\Delta T_{cf}/\Delta T_h < 1$, the tunnel ground temperature starts to exceed the ambient temperature, and it can be considered that part of the smoke has come into contact with the ground and the smoke stratification becomes unstable. In this case, the smoke stratification at this point is located in Region II.

Newman used the method of dimensionless analysis to confirm the function of dimensionless temperature ratio with Froude number, and

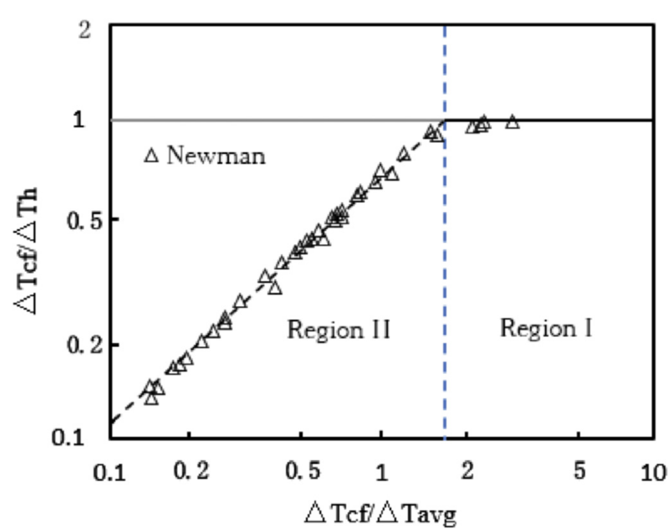

Fig. 2. Temperature stratification as presented by Newman.