Tunnelling and Underground Space Technology 80 (2018) 143–150

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Analysis of entrainment phenomenon near mechanical exhaust vent and a prediction model for smoke temperature in tunnel fire

Lu He, Zhisheng Xu, Hongguang Chen, Qiulin Liu, Yixiao Wang, Yang Zhou*

School of Civil Engineering, Central South University, Changsha, Hunan 410075, China

ARTICLE INFO

Keywords:
Mechanical exhaust
Entrainment
Plug-holing
Smoke temperature
Prediction model

ABSTRACT

To investigate the entrainment phenomenon near a mechanical exhaust vent in the tunnel fire, the computational fluid dynamics method employing the software Fire Dynamics Simulator (FDS) is utilized to analyse the effects of heat release rate (HRR) and exhaust velocity on the entrainment near the vent. The simulation results indicate that the total amount of fresh air entrained in the tunnel increases continuously with increasing HRR and exhaust velocity. However, when the smoke temperature is low, the mass flow rate of fresh air exhausted through the shaft is insensitive to the HRR, while is affected more by the exhaust rate. In addition, a simplified prediction model for downstream smoke temperature is developed to account for the entrainment effect on smoke temperature variation. The predicted values accord well with the simulated ones. Results in this work can provide a reference to the optimization design and management of smoke control system in tunnels.

1. Introduction

Smoke and other poisonous and harmful gases generated by fires accumulate easily inside tunnels owing to the enclosed structure, which can pose a great threat to the safety of trapped staff and firefighters (Alarie, 2002; Babrauskas et al., 1998; Besserre and Delort, 1997; Hietaniemi et al., 1999). Therefore, the design of ventilation and smoke extraction systems is an important part of tunnel fire protection (Du et al., 2015; Liang et al., 2017). These ventilation systems should exhaust smoke promptly and effectively to ensure the safety of trapped people and that rescue operations can proceed smoothly. Mechanical smoke extraction is the most commonly-used smoke exhaust method in tunnels, which is generally efficient and reliable. However, when the mechanical exhaust system is activated, it exerts a significant influence on the flow field near the tunnel ceiling (Huang et al., 2011).

Fan et al. (2013b) conducted a series of subscale experiments and proposed that exhaust from a vertical shaft can cause disturbance at the interface between smoke and fresh air, resulting in direct or indirect entrainment. In a vertical shaft, two-thirds of the total amount of mass flow consists of smoke generated from fire, while some fresh air entrained in the downstream smoke layer is also included. When the mechanical smoke exhaust system is activated, this entrainment owing to the disturbance of flow field becomes more obvious. Ji et al. (2010) found that forty-eight percent of the mass flow through the mechanical exhaust vent is composed of entrained air.

Many studies (Ji et al., 2012; Shi et al., 2003; Vauquelin, 2008; Yi, 2005) pointed out that the occurrence of plug-holing or boundary layer separation does have a significant impact on the performance of smoke extraction. Lougheed and Hadjisophocleous (2001) experimentally determined that when the plug-holing occurs, air entrained in the smoke exhaust vent may reach as high as seventy-five percent of the total mass flow. Ji et al. (2010) found that a greater mechanical exhaust rate and closer distance between the exhaust vent and layer interface result in an increased likelihood of plug-holing, which can reduce the smoke exhaust efficiency. Moreover, the critical Froude number (*Fr*) criterion proposed by Hinkley (1995) to judge the occurrence of plug-holing in natural ventilation can also be applied in the situation of mechanical exhaust system, and a larger critical Froude number correlates to a more serious degree of plug-holing.

The longitudinal temperature distribution is the primary focus in the research of tunnel fire (Fan et al., 2013a; Hu et al., 2006; Kurioka et al., 2003), which will be strongly influenced by the smoke exhaust system. Wang et al. (2015) studied the influence of shaft on the ceiling temperature distribution with model tests. A model proposed by Li et al. (2011) was modified to account for the heat carried by the exhausted smoke, and the results of model tests were determined to be in good agreement with the predicted values.

The entrainment of fresh air in tunnel (Gao et al., 2015) is also one of the most important factors that affects the longitudinal temperature distribution in the smoke layer. Many studies investigated the amount of entrainment that occurs during the one-dimensional horizontal movement experimentally (Jiang et al., 2016; Kunsch, 1998, 2002), and

---

* Corresponding author.
E-mail address: zyzhou@csu.edu.cn (Y. Zhou).

https://doi.org/10.1016/j.tust.2018.06.011
Received 10 December 2017; Received in revised form 22 May 2018; Accepted 17 June 2018

Nomenclature

w	CO_2 mass fraction (mg/kg)
E	heat exhaust coefficient
$\dot{Q}$	heat release rate (MW)
c_p	specific heat at constant pressure (J/g K)
u	velocity (m/s)
D^*	characteristic fire diameter
d	thickness of smoke layer (m)
$\dot{m}$	mass flow rate (kg/s)
H	height of tunnel (m)
W	width of tunnel (m)
L	hydraulic diameter of tunnel (m)
g	gravitational acceleration (m/s^2)
Fr	Froude number
A	cross-sectional area of shaft (m^2)
T	temperature
ΔT	smoke temperature rise

Greek symbols

φ	air mass fraction of smoke exhaust from shaft
η	entrainment coefficient
Δ	deviation property
ρ	density (kg/m^3)

Subscripts

cs	upstream smoke flow
cs'	downstream smoke flow
es	smoke exhausted from shaft
s	smoke
a	fresh air

found that the amount of air entrained in the tunnel during this stage is positively correlated to the relative speed difference between the smoke layer and fresh air. When the smoke extraction system is activated, the entrainment will become more intense due to the increased induced airflow velocity (Jiang et al., 2018b; Vauquelin and Telle, 2005).

At present, researches on the smoke temperature field in tunnel fire mainly focus on the continuous temperature distribution with different boundary conditions, such as inclination and longitudinal ventilation (Ji et al., 2015; Li et al., 2011; Tang et al., 2017). However, the characteristics of temperature difference between upstream and downstream of smoke exhaust vent in the one-dimensional horizontal spreading stage in tunnel fire are rarely involved. And the quantitative analyses on the influence of exhaust vent on the smoke flow field are still lack of attention. Therefore, this study aims to investigate the air entrainment phenomenon due to mechanical exhaust in tunnels, and to quantitatively analyse the influence of exhaust velocity and heat release rate (HRR) on the entrainment of smoke near an exhaust vent. Meanwhile, a simplified prediction model for downstream smoke temperature is developed to account for the entrainment effect. The results of this work can also be used to guide the operation and management of mechanical smoke extraction system in high-rise building fires (Jiang et al., 2018a; Zhou et al., 2018a,b).

2. Theoretical analysis

The corresponding smoke movement in tunnel fire can be divided into five stages (Kunsch, 1998): rising plume, turning region near the ceiling, radial spreading under the ceiling, transition from radial to one-dimensional flow, and one-dimensional flow under the ceiling parallel to the tunnel axis. This study mainly focused on the entrainment phenomenon caused by the presence of smoke exhaust vent during the fifth stage (one-dimensional horizontal spreading). For simplicity, the side of the exhaust vent near the fire source is defined as the upstream side in this paper, while the opposite is downstream. Owing to the suction effect of exhaust system, there is significant entrainment around the vent, where large amounts of fresh air and hot smoke are mixed. The flow field around the exhaust vent is shown in Fig. 1. Some of the fresh air is discharged through the vent, while the other part of undischarged air stays in the smoke layer, mixing with the smoke and spreading downstream.

During the exhaust process, the smoke mass flow rate through the vent and downstream tunnel can be expressed as:

$$\dot{m}_{es} = \dot{m}_{es,s} + \dot{m}_{es,a} \tag{1}$$

$$\dot{m}_{cs'} = \dot{m}_{cs',s} + \dot{m}_{cs',a} \tag{2}$$

The CO_2 concentration in the smoke beneath the ceiling and in the exhaust vent can be used to calculate the mass flow rate of fresh air entrained in the exhaust gas through the shaft as follows (Takeuchi et al., 2017):

$$\frac{\dot{m}_{es,a}}{\dot{m}_{es}} = \frac{\dot{m}_{es} - \dot{m}_{es,s}}{\dot{m}_{es}} \tag{3}$$

$$\dot{m}_{es} w_{es} = \dot{m}_{es,a} w_a + \dot{m}_{es,s} w_s \tag{4}$$

Combining Eqs. (3) and (4):

$$\frac{\dot{m}_{es,a}}{\dot{m}_{es}} = 1 - \frac{w_{es}}{w_{cs}} = \varphi \tag{5}$$

The heat exhaust coefficient, E, is the percentage of heat carried by the smoke discharged from the exhaust port in relation to the amount of heat carried by the upstream smoke. It can be defined as:

$$E = \frac{\dot{Q}_{es}}{\dot{Q}_{cs}} \tag{6}$$

where $\dot{Q}_{cs}$ and $\dot{Q}_{es}$ can be expressed as:

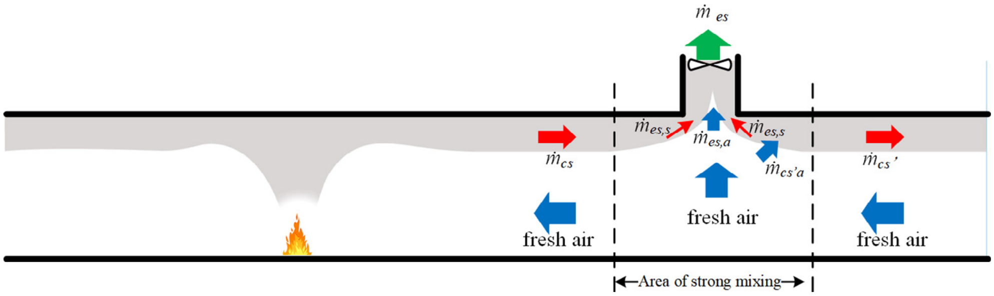

Fig. 1. Flow field around the exhaust vent.