Tunnelling and Underground Space Technology 64 (2017) 95–102

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Characteristics of smoke movement with forced ventilation by movable fan in a tunnel fire

Tiannian Zhou, Jiahao Liu, Qinpei Chen, Xiao Chen, Jian Wang *

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 17 January 2017
Accepted 30 January 2017

Keywords:
Tunnel fire
Movable fan
Ventilation
Smoke movement
Temperature distribution

ABSTRACT

A sequence of experiments involving a fan with varying inclined angles and distances from a fire source were conducted in a full-scale tunnel to investigate the characteristics of smoke movement with forced ventilation by a movable fan. The phenomenon of smoke movement was described by a laser visualization technique, and the backlayering in the presence of ventilation is discussed in this paper. The results of the experiment demonstrate that the distance between the movable fan and the fire source has a critical range, where the effects of smoke exhaust on reducing the maximum temperature under the ceiling and preventing the backlayering are more significant when the fan was placed in this distance range. However, the disadvantage of faster smoke moving downstream is that it might be adverse to a safe evacuation during tunnel fires. In addition, it was determined that the performance of smoke exhaust in a horizontal path was better than that of an inclined angle within a limited distance, but there was no obvious difference when the distances were large.

1. Introduction

The magnitude of tunnel fires has been highlighted by major accidents, including the Tauern Tunnel of Austria (Carvel et al., 2001), the Mont Blanc tunnel joining France to Italy (39 victims) (Barbato et al., 2014), and a subway tunnel in Daegu, Korea (198 victims) (Hu et al., 2007). Smoke is the most deadly factor during fires (Besserre and Delort, 1997). Thus, the development of an effective smoke exhaust method has receive a large amount of attention because it is one of the most important protection measures for personnel safety during evacuation in tunnel fires. In recent years, an increasing number of fire brigades of China have been equipped with a movable jet fan, which is mainly used to improve the environment for rescue and extinguishment in tunnel fires. The operability of the movable fan is better than a fixed fan located at the ceiling because its distance and inclined angle can be freely altered to adapt to the complicated fire scenarios. However, studies on a movable fan have rarely been reported in the previous research (Kim et al., 2006), where some basic data including temperature distribution and smoke propagation velocity were not measured.

To understand the actual efficiency of smoke exhaust for a movable fan, it is necessary to investigate the basic characteristics of smoke movement with the ventilation through full-scale tests. Generally, the process of smoke movement under a tunnel ceiling can be divided into at least three stages: (1) the ceiling jet forming stage, (2) one-dimensional flow forming stage and (3) the smoke descending stage (Hu et al., 2005; Ji et al., 2011). For the second or third stage, the previous studies demonstrated that natural and forced ventilation systems can effectively control the smoke descent and restrain the spread of smoke against longitudinal air flow.

Although the current work is not concerned with natural ventilation, some similar research methodologies in a full-scale tunnel can be applied in the forced ventilation. Natural ventilation with vertical shafts or roof openings can hold back the descent speed of a smoke layer, which is conducive to the safe evacuation of occupants in tunnel fires. Some model-scale experiments (Vauquelin and Megret, 2002; Ji et al., 2012; Kashef et al., 2013; Ji et al., 2014) were conducted to investigate the basic features of smoke movement under the conditions of natural ventilation with vertical shafts. The volume flow rate for smoke extraction was used by Vauquelin and Megret (2002) to assess the efficiency of vertical ducts located at the ceiling under varying heat release rates, locations and shapes of the ducts. To observe the characteristics of smoke movement in a model scale tunnel with vertical shafts, a visualization technique using a laser sheet was employed by Ji et al. (2012). For roof openings, Wang et al. (2009) and Yan et al. (2009) conducted a set of full-scale burning tests in a

---

* Corresponding author.
E-mail address: wangj@ustc.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.tust.2017.01.013
0886-7798/© 2017 Elsevier Ltd. All rights reserved.

two-directional tunnel where its mid-board was separated by walls to assess the possibility of this smoke exhaust method by means of measuring temperature distribution and velocity of smoke spread. Afterwards, Ura et al. (2014) further studied the characteristics of smoke extraction using the same exhaust method but two different median structures: pillars and walls. Likewise, the temperature distribution was the most significant parameter to quantitatively analyze the characteristics of smoke extraction.

In contrast to natural ventilation, the forced ventilation is a more flexible method of controlling the smoke spread for longer tunnels (Li and Chow, 2003). The diversification of organization types is a main feature for forced ventilation, which includes longitudinal, transverse and semi-transverse ventilation types. In the current application, the movable fan belongs to a longitudinal ventilation type, for the main purpose of preventing the smoke movement against the wind flow direction in tunnel fires. Before discussing smoke flow with longitudinal ventilation, an important concept has to be reviewed: the critical velocity that is defined as the minimum wind velocity required to suppress upstream spreading of smoke (Kunsch, 1999). This means a satisfactory ventilation system should supply a wind flow not less than the critical velocity to avoid the backlayering phenomenon (Barbato et al., 2014). It is easier for firefighters to rescue trapped people and extinguish the fire in the presence of a continuously blowing ventilation system. In general, the critical velocity is dependent on the heat release rate of the fire and the geometric shape of the tunnels (Wu and Bakar, 2000), but the dimensionless critical velocity is approximately constant when the dimensionless heat release rate is large enough (Li et al., 2010). Hence, the critical wind velocity provided by forced ventilation for different fire scenarios is a significant reference associated with the capacity selection of fans and even the early design of ventilation systems. Prior studies on the critical velocity were conducted in scale model tunnels where the wind velocities for the whole cross-section were identical. However, a jet fan cannot guarantee the same velocity on the cross-section of full-scale tunnels, resulting in a challenge to the critical velocity theory. Therefore, its application in movable fan needs to be discussed.

A movable fan is normally installed on a large vehicle and can conveniently adjust its distance from the fire and its inclined angle. However, if the distance between the movable fan and the fire source is too far, the ventilation produced by the jet fan is unable to prevent the backlayering of smoke. In contrast, if the distance is too close, the same phenomenon can also occur because the jet fan leads to the secondary flow in the vicinity of the tunnel ceiling. On this basis, Kim et al. (2006) gave a suggested minimum installation distance of 25 m for the jet fan through a set of scale model experiments. Note that this is the critical distance to ensure the stability of the smoke layer. Se et al. (2012) employed the CFD technique to investigate the influence of the distance of jet fan groups located on the ceiling on the airflow structure, and the results showed that the upstream velocity had a levelling-off effect when active fan group is placed 200 m or more from the fire source. Likewise, a numerical analysis was conducted to evaluate the influence of a pitch angle of the fixed jet fan located on the ceiling (Betta et al., 2009; Musto and Rotondo, 2014) or the sidewall (Chammem et al., 2014) on the performance of the longitudinal ventilation, and the results showed that there exists an optimal pitch angle to minimize the pressure loss and produce the maximum induced air flow rate. However, prior studies in varying distances and angles of a jet fan have focused on a fixed fan installed on the ceiling or sidewall of tunnels. Hence, a method for controlling these properties of a movable fan in a full-scale tunnel fire is still worthy of research. Consequently, the critical velocity can be determined and the best efficiency of smoke exhaust can be achieved.

The objective of this study is to understand the characteristics of smoke movement with varying distances and inclined angles of the movable fan that contribute to the performance evaluation. For this purpose, a set of full-scale tests were conducted in a road tunnel. Meanwhile, the temperatures beneath the ceiling were measured and the smoke trail exposed to a laser sheet was recorded by a digital video.

2. Experimental set-up

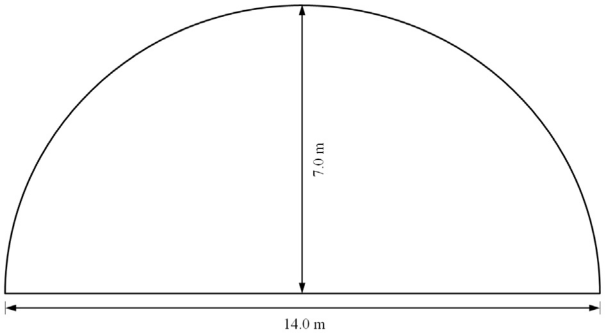
2.1. Tunnel configuration

The full-scale experiments were conducted in the Ziyin Road Tunnel at Zunyi city, Guizou province of China, as shown in Fig. 1(a). The total length of the tunnel is 600 m, including a 305 m straight section and a 295 m curved section. To simplify the measurements, the straight region was selected as the test section. The cross section of the tunnel ceiling is a semicircular structure and its dimensions are shown in Fig. 1(b). The maximum width of the tunnel is 14 m and the maximum ceiling height is 7 m.

2.2. Fire source

The fire source was arranged 180 m away from the open end of the straight section and was placed at the centerline of the tunnel. Considering the tunnel close to downtown, industrial ethanol (purity of 98%, combustion efficiency of 0.92 (Hamins et al., 1999), complete heat of combustion of 26.8 kJ/g (Rakopoulos et al., 2011)) was selected as fuel for the pool fires because its combustion products contain very little soot in the process of burning. The heat release rate (HRR) Q of fire source can be calculated according to the following correlation:

(a) Photography of the entrance



(b) Dimensions of cross section

Fig. 1. Cross-section of the experimental tunnel. (a) Photography of the entrance. (b) Dimensions of cross section.