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Numerical study on the smoke control using point extraction strategy in a large cross-section tunnel in fire

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ABSTRACT

The Point Extraction System (PES) is effective for smoke control and popular for long and large cross-section shield TBM (Tunnel Boring Machine) tunnels. To clearly comprehend the fire characteristics on the cross-section and correctly apply the smoke control strategy, a series of 3D numerical Computation Fluid Dynamics (CFD) simulations are conducted. Smoke temperature, minimum visibility and carbon monoxide (CO) concentration are analyzed to evaluate the efficiency and effect of the PES on the evacuation environment according to the standard safety criteria. Three fire scenarios i.e. 5 MW, 20 MW, and 50 MW are employed in the simulations. Fire characteristics and smoke control in different transverse fire locations, dimensions of smoke exhaust openings and smoke exhaust rate are simulated, respectively. The results indicate that transverse fire location slightly affects the evacuation environment due to the nature of large cross section. With the same area, the slender exhaust opening perpendicular to the longitudinal direction of the tunnel can control the smoke better than the short one, especially in the areas far away from the fire source. The smoke extraction efficiency of PES is determined by the smoke exhaust rate. Higher smoke exhaust rate improves the smoke control efficiency to a large extent.

1. Introduction

With the increase in traffic volume, the chance of tunnel traffic accidents and associated fires has increased, which leads to great risk to human life and damage to property and economy. Fires usually result in the significant accumulation of hot smoke in the tunnel because of the confined space and insufficient exits. It is extremely hazardous for drivers and rescue teams due to the rising temperature, the reduced visibility and high content of carbonic monoxide (CO). Tunnel disasters, such as the accidents in the Mont Blanc Tunnel in 1999 and in the San Gottardo Tunnel in 2001, have demonstrated the challenges of emergency evacuation and rescue (Vega et al., 2008), and strict demand for effective smoke control in tunnel fires. It is necessary and indispensable to design a reasonable smoke control strategy to prevent potential fires in a long and large tunnel. Smoke control strategies and ventilation systems should ensure that tunnel users can escape safely under smoke exposure.

Various smoke control systems are developed to extract smoke at fire emergency, e.g. longitudinal extraction systems, point extraction system (PES) and natural extraction system, etc., from which, longitudinal extraction systems and PES are the most commonly adopted methods in long road tunnels. As shown in Fig. 1(a), in longitudinal extraction strategies, longitudinal flow, along with the direction of traffic flow to prevent recirculation of gas flow, is produced by jet fans on the top of tunnels and it can control the smoke flow towards downstream. It provides large amount of oxygen necessary in burning during the process of controlling the smoke and decreases the visibility in tunnels, which does harm to evacuation and escape. Cong et al. put forward a method to improve the smoke extraction efficiency of natural ventilation with vertical shaft in 2018. Furthermore, as exhibited in Fig. 2, in PES, a typical method used in long shield TBM (Tunnel Boring Machine) tunnel, fresh air is induced by jet fans located under the exhaust duct, to dilute vehicle exhaust gases in normal situation. The exhaust duct remains closed in normal situation and is only used to exhaust smoke produced by fire. Once fire occurs, a number of exhaust openings near the fire source will be activated to keep the smoke at the top of the tunnel cross-section; smoke would then be extracted through the duct to the outside of the tunnel by the exhaust fans. The PES has

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Nomenclature

CFD	Computation Fluid Dynamics
HRR	Heat Release Rate
PES	Point Extraction System
SHR Tunnel	South Hongmei Road Tunnel
CS1	cross section 1 of tunnel (10 m away from fire source), which represents the conditions near the fire source
CS2	cross section 2 of tunnel (25 m away from fire source), which is right under the smoke exhaust openings
CS3	cross section 3 of tunnel (50 m away from fire source), which represents the conditions far away from the fire source
LEC	Light Extinction Coefficient
Q	Heat Release Rate of the fire source (kW)
α	coefficient of fire source developing model (kW·s^{-2})
t	fire duration time from ignition (s)
Y_{smoke}	smoke production of the fire (kg/s)
β	constant (kg·s^{-3})
Y_{co}	yield of CO of the fire source (ppm)
A_1	yield of CO at well ventilation condition (ppm)
a_1, a_2, a_3	constants
ϕ	Local Equivalence Ratio
ξ	mixture fraction
ξ_{st}	stoichiometric mixture fraction values
S_{smoke}	visibility within the tunnel (m)
k_{smoke}	light extinction coefficient (m^{-1})
C	non-dimensional constant characteristic of the type of object being viewed through the smoke
T_{smoke}	smoke temperature within tunnel (K)
T_{smoke}^{max}	maximum temperature under the exhaust duct plate (at height of 6.5 m) (K)
λ	coefficient of temperature variation, which is defined to reflect the change rate of temperature in other groups compared to Group-I (set as the standard group)
$T_{Group-i}$	temperature at 2.0 m or 6.5 m high for cases in Group-*i* (K)
$T_{Group-I}$	temperature at 2.0 m or 6.5 m high for cases in Group-I (K)
h	height from road surface of tunnel (m)

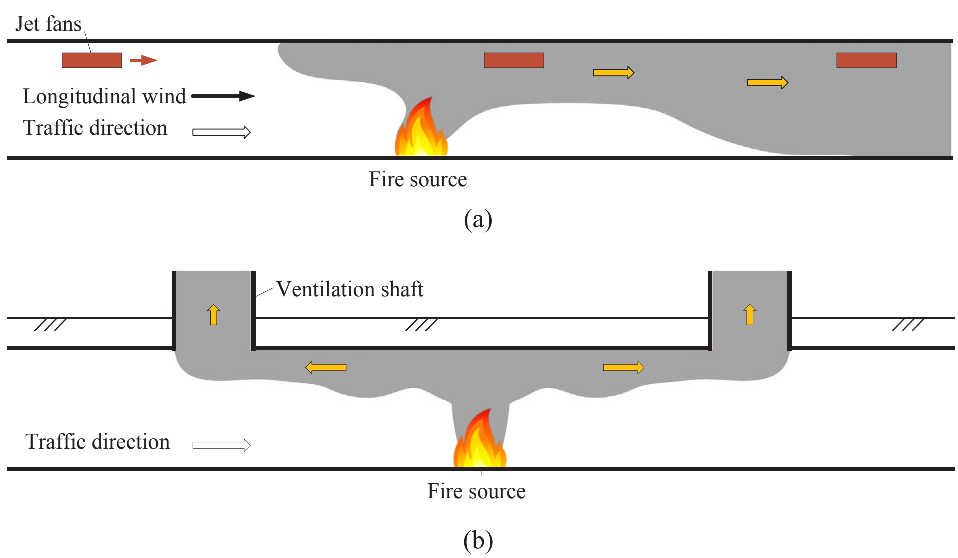

Fig. 1. Schematic diagram of smoke control systems. (a) Longitudinal extraction system; (b) Natural extraction system.

obvious advantages in case of traffic jams and fire situations (including multiple fire sources) since it operates exhaust openings near the fire source in a fire emergency situation to restrict the smoke in a relative certain area. Jiang et al. (2018) studied induced airflow velocity of point smoke extraction in road tunnel fires and focused on the research of smoke back-layering length. Tang et al. (2018) did experiments in a horizontal channel to investigate the longitudinal thermal plume temperature distribution of buoyancy-driven ceiling jet beneath the ceiling using ceiling smoke extraction. The PES becomes a mainstream approach to control smoke in tunnel fires. In this study, the PES is applied in the tunnel in case of fire.

Many previous experimental and numerical studies on tunnel fire ventilation have been conducted (Woodburn and Britter, 1996a,b; Hu et al., 2006; Lin and Chuah, 2008; Yoon et al., 2009; Cong et al., 2017). A description and comparison of different tunnel ventilation systems was completed by Li and Chow (2003) using Computational Fluid Dynamics (CFD). Lin and Chuah (2008) investigated the performance of different smoke extraction strategies for a long vehicle tunnel under a 100 MW fire load and found that the single-point extraction opening system was more effective than the multi-point extraction opening system. Yoon et al. (2009) utilized a CFD modeling tool to find the optimal exhaust flow rate for the vertical shaft that can confine the smoke and investigated whether the designed vertical shaft can limit smoke propagation from a fully loaded gasoline tank lorry fire. Ballesteros-Tajadura et al. (2006) analyzed the influence of slope on the semi-transversal ventilation system of an urban tunnel during possible fire incidents by using FLUENT with a simulation that covered 15 min. Zhu et al. (2016) conducted the numerical study on the feasibility and efficiency of point smoke extraction strategies in a large cross-section tunnel. Mei et al. (2017) studied and calculated smoke layer length and thickness in tunnel fires with ceiling extraction and multiple point extraction respectively Hu et al. (2014) and Tang et al. (2016a,b) investigated thermal smoke back-layering flow length and buoyant flow stratification behaviors, did an experiment to investigate and put forward a modified model to predict the maximum temperature of smoke flow with the combined effect of ceiling mechanical exhaust system and longitudinal ventilation. Under the same condition, Li et al. (2016) conducted a series of experiments to study the smoke thermal stratification. Wang and Wang (2016) set a numerical simulation to investigate the effects of cross-sectional fire locations on the critical velocity and the smoke flow characteristic in a longitudinal ventilation tunnel. Yao et al. (2017) studied maximum smoke temperature beneath the ceiling in an enclosed channel with different longitudinal fire locations both experimentally and theoretically. Zhong et al. (2015) did