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Experimental study on maximum smoke temperature beneath the ceiling induced by carriage fire in a tunnel with ceiling smoke extraction

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ABSTRACT

Tunnel fire is an important topic considering tunnel safety design and regulations, a process in which the high smoke temperature under the ceiling is the key parameter. This paper investigates experimentally the maximum temperature beneath the ceiling induced by carriage fire in a tunnel with ceiling smoke extraction, which have been studied in the past. A series of small scale experiments are conducted in a model tunnel, consisting of a carriage (with an opening) in a tunnel. A range of ceiling smoke extraction rates, and heat release rates are considered. The maximum temperature is measured, and shows different development trends with increasing ceiling smoke extraction rate. Maximum temperature measurement without ceiling smoke extraction shows some deviation with previous model predictions, which mainly can be explained by the effect of stack effect, induced by narrow channels, and wall entrainment restrictions. This study also revealed the variation characteristics of ceiling maximum temperature with different ceiling smoke extraction rates. A correlation was proposed to describe the maximum temperature beneath ceiling induced by carriage fire in a tunnel with ceiling smoke extraction, which is a piecewise function. These results and correlations are new and a significant improvement over previous results in the literature.

1. Introduction

1.1. Literature review and previous basic model

In recent years, the construction of ventilated tunnel has developed rapidly (Ingason, Li, Lönnermark, & Fire, 2015; Zhu et al., 2015). In case of tunnel fire accident, smoke is an important factor causing death in tunnel fire (Caliendo, Ciambelli, Guglielmo, Meo, & Russo, 2013; Du, Yang, Wei, & Zhang, 2018; Guo, Yuan, Fang, & Wang, 2013; Lönnermark & Ingason, 2005; Tang, Li, Mei, & Dong, 2016; Yang, Ding, Du, Mao, & Zhang, 2018). The characteristics of smoke spread have been a hot research topic in the longitudinal ventilated tunnel or tunnel-like underground buildings by numerical simulation ((Edmund) Ang, Rein, Peiro, and Harrison, 2016; Collela, Rein, & Torero, 2011; Fletcher & Kent, 1994; Gannouni & Ben Maad, 2017; Gao, Liu, Chow, & Fong, 2004; Harish & Venkatasubbaiah, 2014; Król & Król, 2018; Lee & Ryou, 2006; Wang & Wang, 2016; Xie et al., 2018) and experimental study (Li, Zhang, Hu, & Gao, 2014; Yang, Huo, Zhang, Zhu, & Zhao, 2012; Yi et al., 2015). It should be noted that, the maximum smoke temperature beneath ceiling is an important research parameter in a tunnel or tunnel-like underground buildings, the fire-induced maximum smoke temperature under the ceiling have an important influence on the personnel evacuating. Meanwhile, it also will affect tunnel facilities.

The work on maximum smoke temperature beneath ceiling started from (Alpert (1972)) which proposed empirical models to describe the maximum smoke temperature beneath an unconfined ceiling. Zhang et al., (Zhang, Guo, Tao, & Liu, 2017) investigated the maximum smoke temperature beneath an unconfined ceiling with different inclination angles induced by rectangular fire source. (Delichatsios (1981)) conducted experiments to study the smoke temperature profile under a beamed ceiling.

For the maximum smoke temperature beneath ceiling in a tunnel or tunnel-like underground buildings, many studies have been done in the past (Gao, Ji, Fan, & Sun, 2015; Hu, R, Peng, Chow, & Yang, 2006; Ji, Fan, Zhong, Shen, & Sun, 2012; Kurioka, Oka, Satoh, & Sugawa, 2003; Li, Lei, & Ingason, 2011; Zhou, He, Lin, Wang, & Wang, 2017), including the natural ventilation and longitudinal ventilation. (Kurioka et al., 2003) studied the maximum smoke temperature rise under ceiling in ventilated tunnel and built the prediction model. (Hu et al. (2006)) investigated the maximum smoke temperature by full-scale tunnel fire tests and CFD numerical simulations. In 2011, (Li et al. (2011)) analyzed maximum smoke temperature in the model scale tunnels, including considering varying fire heat release rates, crosswind velocities, finally proposed the dimensionless description model, when

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Nomenclature

C_p	Specific heat (kJ/kg/K)
$\Delta T_{\max,v}$	Maximum temperature rise with ceiling extraction (K)
D	Horizontal distance between fire source and the tunnel sidewall (m)
u'	Dimensionless ventilation velocity (-).
g	Acceleration of gravity (m/s^2)
v	Ceiling extraction velocity (m/s)
H_d	Distance from burner face to tunnel ceiling (m)
$V*$	Dimensionless ceiling extraction velocity
$\dot{m}_a$	The mass flow rate into carriage (kg/s)
W	Tunnel width (m)
$\dot{Q}$	Heat release rate (kW)

Greek letters

$\dot{Q}_{conv}$	External total heat release rate which controls the external temperature (kW)
ρ	Smoke density under the exhaust port (kg/m3)
$\dot{Q}_{ex}$	Excess heat release rate (kW)
ℓ	The size of the tunnel
S	outlet area

Subscripts

T	Smoke temperature (K)
F	Full scale
T_a	Ambient temperature (K)
M	Model scale

dimensionless ventilation velocity $u' \le 0.19$, including no longitudinal ventilation, the dimensionless description model can be expressed in Eq. (1)

$$\Delta T_{\max} = 17.5\frac{\dot{Q}}{H_d^{5/3}} \quad u' \le 0.19 \tag{1}$$

where $\Delta T_{\max}$ stands for the maximum smoke temperature rise under the ceiling (K), $\dot{Q}$ is the fire heat release rate (kW), H_d is the vertical height between fire source and tunnel ceiling (m), u' is the dimensionless ventilation velocity.

(Ji et al. (2012)) and (Gao et al. (2015)) conducted the model tunnel experiments with size of 6 m long, 2 m wide and 0.88 m high. They studied the effect of horizontal fire source location on the maximum smoke temperature in the tunnel fires, including wall fires in a tunnel, and (Ji et al. (2012)) proposed the corresponding empirical description model.

$$\Delta T_{\max} = 17.9\frac{\dot{Q}^{2/3}}{H_d^{5/3}}(1.096e^{-14.078D/(W/2)} + 1). \tag{2}$$

(Zhou et al. (2017)) also investigated the influence of different transverse fire locations on smoke maximum temperature under the arc-shaped ceiling by Fire Dynamics Simulator (FDS) simulations, developed by the National Institute of Standards and Technology (NIST) (McGrattan et al., 2015).

$$\Delta T_{\max} = 17.5\frac{\dot{Q}^{2/3}}{H_d^{5/3}}(2.19e^{-16.42D/(W/2)} + 0.97). \tag{3}$$

In recent years, with the rapid development of the smoke control technology in tunnel fires, smoke extraction ventilation become more common for the long and large cross section tunnels. Now it is an important research topic, a few studies have been done in the past (Hu, Chen, & Tang, 2014; Ingason & Li, 2011; Ingason et al., 2015; Mei, Tang, Ling, & Yu, 2017; Tang, Li et al., 2017; Zhu, Shen, Yan, Guo, & Guo, 2016). (Hu et al. (2014)) conducted a series of model experiments to analyse the effect of ceiling smoke extraction on the temperature profile under the ceiling. In 2016, (Zhu et al. (2016)) studied the feasibility and efficiency of point smoke extraction strategies in large cross-section shield tunnel fires by CFD simulations.

1.2. The motivation of this work

Based on the literature review above, most previous tunnel fire researches consider in default that the tunnel fire scene is induced by free fire source, such as liquid oil pan fire or gas burner. In addition, some

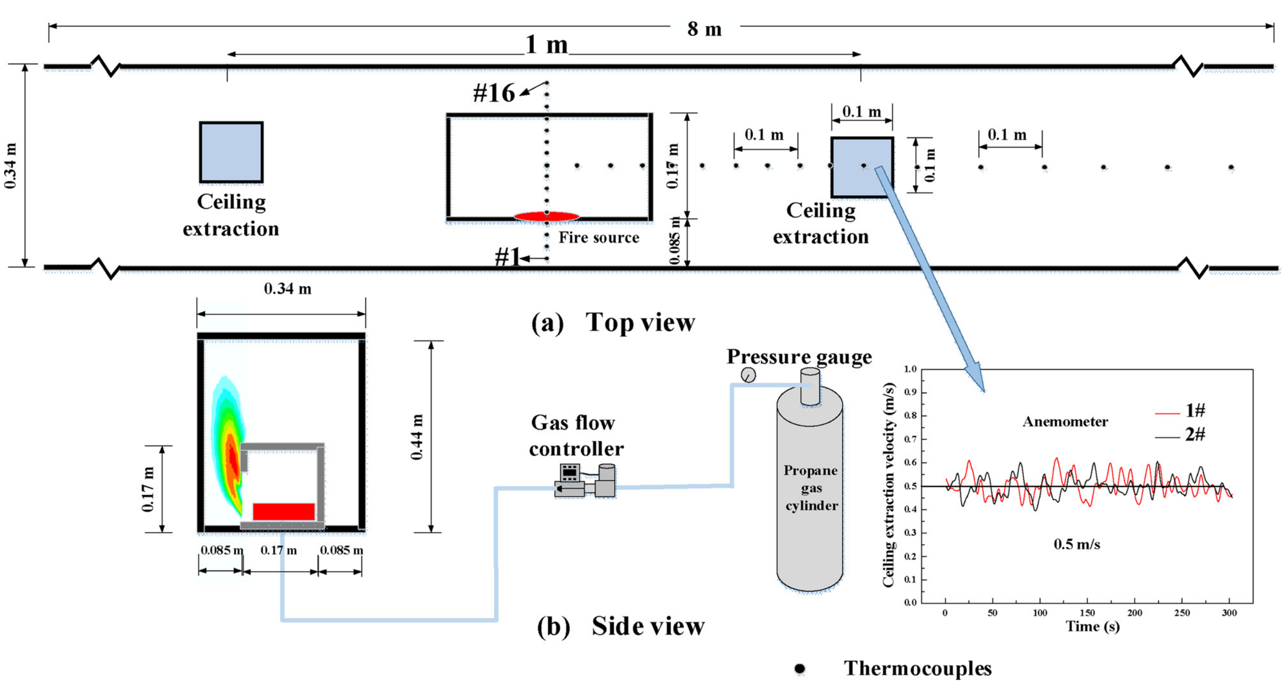

Fig. 1. Schematic of model tunnel.