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Research Paper

Influence of constraint effect of sidewall on maximum smoke temperature distribution under a tunnel ceiling

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HIGHLIGHTS

- Fire experiments and simulations carried out in a full-scale tunnel.
- Maximum smoke temperature data beneath ceiling obtained with constraint effect.
- Transverse distance factor is included into the current equations.
- Modified correlation agrees with the previous data.

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ABSTRACT

A sequence of tests and simulations with varying transverse fire locations were conducted in a full-scale tunnel to investigate the constraint effect of sidewall on the maximum smoke temperature distribution under a tunnel ceiling. Then, the simulated results were comprehensively compared with both those of the full-scale tests and the model-scale experiments from previous studies. The results of the full-scale experiment show that the longitudinal maximum smoke temperature rise distribution decreases can be approximated by a power function. However, the numerical simulation results indicate that an exponential distribution may be plausible. The normalized ceiling jet temperature rise at the impingement point displays an exponential variation with the distance between the fire source and the sidewall. Meanwhile, regression models taking the constraint effect of sidewall into account was developed to predict the ceiling jet impingement temperature in tunnel fires.

1. Introduction

The loss of human life and the damage to tunnel infrastructure are the two main types of hazards during road tunnel fires [1]. The fires in the Tauern Tunnel in Austria, the Mont Blanc Tunnel joining France to Italy and the Channel Tunnel joining the UK to France have highlighted the magnitude of the tunnel fires [2]. Meanwhile, the propagation patterns and the maximum temperature distribution of the fire-induced smoke play particularly important roles in the safe evacuation of occupants. The high-temperature smoke can have a direct or indirect effect on the destruction of the tunnel infrastructure, facilities and vehicles [3]. Thus, it is necessary to pay more attention to the maximum smoke temperature distribution under a ceiling in road tunnel fires.

Alpert [4] proposed a couple of empirical formulas in power function form to predict the radial maximum smoke temperature and velocity distributions for a given heat release rate (HRR) under an unconfined ceiling. A simple method involving the Alpert model [4] was proposed by Ji [5] to predict the maximum smoke temperature under a confined ceiling in a model-scale subway station. Delichatsios et al. [6] discovered that the dimensionless temperature decreases exponentially with the dimensionless distance when the fire source was placed at the centerline between two beams. Compared with the full-scale experimental data, Delichatsios' model was found to over-estimate the rate of decay of the ceiling-jet temperature for downstream flow in tunnel fires [7]. Although two types of typical models, the power model [4] and the exponential model [6], were used to fit the distribution correlation of the maximum smoke temperature under a ceiling, the applicability and difference between these models in full-scale tunnels have not been discussed in depth. Kurioka et al. [8] conducted a series of experiments in multiple model tunnels and then

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Nomenclature

A, B, C	coefficient for constants in Eq. (11)
a, b, c	coefficient for constants in Eqs. (12) and (16)
b_{fo}	radius of the fire source (m)
c_p	heat capacity of air (kJ/(kg K))
d	transverse distance between fire source and the nearest sidewall (m)
D_{eff}	effective diameter of the fire source (m)
g	gravitational acceleration (m/s^2)
H	tunnel height (m)
$\bar{H}$	hydraulic tunnel height (m)
H_{ef}	vertical distance between fire source bottom and tunnel ceiling (m)
l	beam spacing (m)
Q	heat release rate (kW)
Q_c	convective heat release rate (kW)
Q^*	dimensionless heat release rate (–)
Q'	modified heat release rate in Eq. (15) (kW)
r	longitudinal distance from the fire source (m)
St	Stanton number (–)
S	cross-sectional area of tunnel (m^2)
$\Delta T_{\max}$	maximum smoke temperature rise beneath the ceiling (°C)
T_a	ambient temperature (°C)
$T_{r,\max}$	maximum ceiling smoke temperature along the longitudinal direction (°C)
V	longitudinal ventilation velocity (m/s)
V'	dimensionless ventilation velocity (–)
w	tunnel width (m)
W	wetted circumference (m)
z_H	distance of ceiling above the base of a burning fuel array (m)
z_v	distance of virtual plume origin above the base of a burning fuel array (m)

Greek symbols

β	empirical coefficient (–)
ρ_a	ambient density (kg/m^3)

Subscripts

0	above fire
c	fire located at the longitudinal centerline
d	transverse distance between fire source and the nearest sidewall
f	full-scale tunnel
m	model-scale tunnel
r	longitudinal distance from the fire source
∞	free from impact of the sidewall

generalized an empirical formula to estimate the maximum smoke temperature rise under a tunnel ceiling. Compared with full-scale burning experiments conducted by Hu et al. [9], their results agreed fairly well with Kurioka's equations. However, the details of maximum smoke temperature distribution were not presented in Kurioka's equations. In addition, a global model on temperature distribution beneath a tunnel ceiling was developed by Hu et al. [10,11] to take the combination of point extraction and longitudinal ventilation into account.

In recent years, Li and Ingason et al. [12–15] conducted a relatively comprehensive research on the maximum ceiling gas temperature through model-scale tests and reanalysis of the large scale tunnel fire tests that have been performed worldwide. The results showed that the maximum ceiling excess gas temperature can be divided into two piecewise regions as a function of the fire size, the ventilation and the effective tunnel height by the dimensionless ventilation velocity 0.19, namely: linear increase period and a constant period. On this basis, Hu et al. to further investigate the influence of sloping effect [16] and blockage effect [17,18] with longitudinal ventilation on the maximum gas temperature beneath a tunnel ceiling and then improved Li's equations [15].

A fire is usually assumed to take place in the centerline of the tunnel in most previous studies [13–22]. In wide multi-lane tunnels, traffic accidents and the associated fires may not occur along the centerline of the tunnels. When the fire source is closer to the sidewall, the confined space of the tunnels may affect the maximum gas temperature distribution under the ceiling such that it affects the layout of hardware, such as smoke detectors, heat detectors and sprinklers, associated with detection and suppression of tunnel fire. In their tunnel fire studies, Wang [23] and Yan [24] set the fire sources near the sidewall in full-scale tunnel tests with roof openings. However, the transverse fire location was considered only in one situation. Ji and Fan et al. [25,26] conducted a series of model-scale tunnel fire experiments and found that the maximum ceiling smoke temperature was higher than that under the unconfined ceiling and, because of the constraint effect of the tunnel sidewall, that the decrease rate of the maximum temperature along the transverse direction was larger than that along the longitudinal direction. Gao et al. [27] further characterized the effect of different transverse fire locations and proposed that the maximum ceiling gas temperature varies as the 1/2 power of a modified dimensionless energy release rate, taking the heat release rate and effective ceiling height into account. Some recent related papers about the sidewall effect on fires have been published [28–31]. However, for different transverse fire locations, the full-scale experimental data of longitudinal maximum temperature at the centerline were not reported in previous studies. In addition, the influence of the constraint effect of sidewall on the maximum ceiling smoke temperature needs to be verified to determine whether the conclusions from the model-scale experiments [25–27] can be extended to full-scale tunnel fires. Hence, it is essential to focus on full-scale scenes to further explore the distribution of the maximum ceiling smoke temperature with varying transverse fire locations.

In the current study, full-scale tests and numerical simulations were conducted to investigate the maximum smoke temperature distribution beneath a tunnel ceiling. A sequence of full-scale tests with two transverse fire locations were carried out, excluding a wall fire to avoid damaging the sidewall of the newly built tunnel that was covered with decoration. Based on the full-scale experimental data, the applicability and difference between the power model and exponential model were analyzed and compared. The distribution of the longitudinal maximum ceiling smoke temperature was also presented. To compensate for the limited number of full-scale tests, numerical simulation was adopted to add more transverse fire scenarios, including wall fires where the fire source abuts the sidewall. The results from the numerical simulation were used to compare with those of the full-scale tests and the data in previous reference. A quantitative analysis correlating the transverse fire locations and the maximum smoke temperature rise under the ceiling were then examined in detail by conducting a dimensional analysis.