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Maximum temperature of smoke beneath ceiling in tunnel fire with vertical shafts

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ABSTRACT

To assess the impact of heat smoke in tunnel with vertical shafts, the maximum temperature of smoke beneath ceiling is researched theoretically and experimentally in this paper. A theoretical prediction model for maximum temperature of smoke beneath ceiling is built using dimensional analysis. A numerical model is built and calibrated with the full-scale experiment data. The calibrated numerical model is used to simulate the maximum temperature of smoke under different conditions with different shaft geometry. At last, the proposed theoretical model was formulated and compared with Kurioka model, experimental data and simulation data. The results show that the proposed theoretical model can give a better prediction for the tendency. It can be used to predict the maximum temperature of smoke beneath ceiling of tunnel with vertical shafts by taking the shaft geometry and arrangements effect into account.

1. Introduction

In tunnel fires, high temperature smoke and heat are normally difficult to be discharged effectively. They threaten the safety of the trapped people and tunnel structure. According to statistics, concrete structure may crack and collapse when the temperature is at 500 °C and above as the mechanical properties of concrete will change. Not only will they hinder the rescue operation, but also lead to destruction of the tunnel structure. Recently, tunnel fires have induced some disasters, such as, fires in channel tunnel joining the UK and France hurting 34 people. Submarine Tunnel fire of England killed 20 people and caused the roof collapse. Fire accident illustrations are shown in Figs. 1 and 2. Studies on thermal flow dynamics and characteristics in tunnels have received focused attention in recent years, as a special thermal engineering problem (Chen et al., 2015; Tang et al., 2014, 2013; Chen et al., 2013; Hu et al., 2010).

Extensive works have been reported in the literatures to address the maximum temperature of smoke beneath ceiling. For instance, Kurioka et al. (2003) proposed the empirical formula for maximum temperature of smoke layer, based on the correlation of scale-model experimental results. Moreover, Hu et al. (2006) and Wang et al. (2007) justified the model by a set of full-scale fire experiments. Hu et al. (2013a,b) proposed the empirical correlations by incorporating the tunnel slope factor into Kurioka model. Based on fire plume theory and experimental results, Li et al. (2011) proposed a formula for predicting the maximum gas temperature. Further, correlations for the maximum temperature in the vicinity of fire source are proposed for low and high ventilation (Li and Ingason, 2012). Meanwhile, (Ji et al., 2011; Fan et al., 2013) established a simplified calculation method involving the Alpert equation by taking the end wall effect into account. Gao et al. (2014) developed an empirical formula to predict the maximum temperature for small fires, taking fire location, heat release rate, and geometry of tunnel into account. However, there are only a few preliminary studies on the maximum temperature in tunnel fire with natural ventilation. Through full-scale experiments and Computational Fluid Dynamics (CFD), author of this paper (Wang et al., 2009a,b) investigated the smoke characteristic in tunnel with natural ventilation. Kashef et al., 2012 designed a series of experiments, using a 1:15 model tunnel, to investigate the influential parameters on temperature distributions in tunnel fires with natural ventilation.

Although aforementioned researches do provide reliable information and has been receiving attentions, no theoretical analysis have been performed on the maximum smoke temperature in tunnel fire with vertical shafts. This paper discusses and proposes a model of maximum smoke temperature beneath ceiling in tunnel fire with vertical shaft, especially for multiple shafts.

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Nomenclature

A_s	cross-sectional area of model tunnel (m^2)
A_f	area of fire source (m^2)
H_d	height from the surface of fire source to tunnel ceiling (m)
L	distance from the position that flame and/or hot current axis impinged on the tunnel ceiling to the center of fire source (m)
Q	heat release rate (KW) (7.5 MW)
ρ_a	density of air (1.29 kg/m^3)
T_a	temperature of air
V	representative longitudinal ventilation velocity
C_p	specific heat at constant pressure (1003.2 J/(k kg))
E_Q	ratio of heat release rate over natural wind energy
F_T	aspect ratio of thermal energy over buoyant static energy

2. Theories

There are too many parameters influencing the maximum temperature beneath ceiling in tunnel with vertical shafts to establish a simplified calculation model. In this section, dimensionless analysis is adopted to analyze the maximum smoke temperature beneath ceiling in tunnel fire with vertical shafts. Based on the dimensionless analysis, a theoretical model to predict the maximum temperature of smoke beneath ceiling in tunnel fire with vertical shafts is developed.

2.1. Kurioka model

In the case of the flame not impinging on the tunnel ceiling, Kurioka attempts to develop a formula for flame inclination, as shown in Fig. 3, based on the following assumptions (Kurioka et al., 2003).

(a) Shape of fire source is square or circular.
(b) Extension of the flame base by forced ventilation is negligible.
(c) Cross-sectional shape of tunnel is a rectangle.
(d) Opening length, $\sqrt{A_s}$ for the mass flux flowing into the tunnel through the opening and length of fire source, $\sqrt{A_f}$ for that carried by the inclined fire plume are respectively adopted as a reference length.
(e) Moderate forced ventilation is operating, namely not becoming one well-mixed layer, but upper hot and lower cold layers are formed.

Based on the above assumptions, it is obtained as follows that a formula for the distance from the center of burner surface to the position that the maximum temperature of smoke layer beneath ceiling:

$$\frac{L}{H_d} \propto \left(\frac{A_s}{A_f}\right)^{\frac{1}{2}} Fr^{\frac{1}{2}} Q^{*2\eta-\frac{1}{5}} \tag{1}$$

Kurioka derived one empirical equation to predict the maximum smoke temperature rise beneath the ceiling based on reduced-scale experiments, as follows:

$$\frac{\Delta T_{\max}}{T_a} = \gamma \left(\frac{Q^{*\frac{2}{3}}}{Fr^{\frac{1}{3}}}\right)^{\varepsilon} \tag{2}$$

$$\text{When} \begin{cases} \frac{Q^{*\frac{2}{3}}}{Fr^{\frac{1}{3}}} < 1.35: & \gamma = 1.77, \varepsilon = 6/5; \\ 1.35 \leqslant \frac{Q^{*\frac{2}{3}}}{Fr^{\frac{1}{3}}}: & \gamma = 2.54, \varepsilon = 0; \end{cases}$$

where $Q^* = \frac{Q}{\rho_a C_p T_a g^{\frac{1}{2}} H_d^{\frac{5}{2}}}$; $Fr = \frac{v^2}{gH_d}$

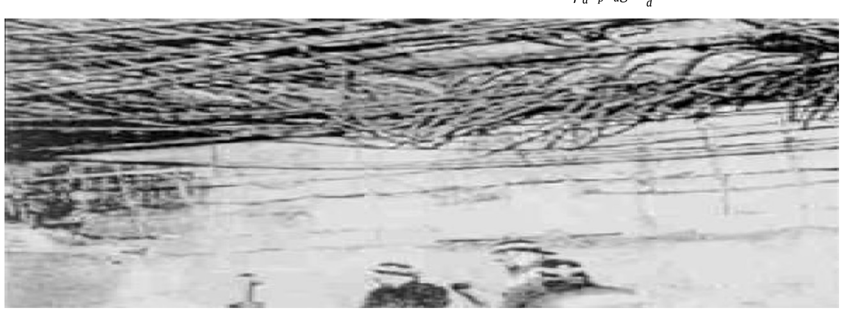

Fig. 1. Moorfleet tunnel of German.

Fig. 2. Submarine tunnel of England.