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The maximum ceiling gas temperature in a large tunnel fire

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ABSTRACT

Effects of different ventilation systems, ventilation velocities, heat release rates, tunnel geometries and fire sources on the maximum excess gas temperature beneath the ceiling in large tunnel fires are analyzed. Data from numerous model scale tests and most of the large scale tunnel fire tests that have been performed worldwide are used and analyzed. Correlations for the maximum ceiling excess gas temperature in the vicinity of the fire source are proposed for low and high ventilation flows. The temperature data indicate two regions, depending on the dimensionless ventilation velocity. Each can be divided into two sub-regions. The first sub-region exhibits linear increase which transits into a constant period, depending on the fire size, ventilation and the effective tunnel height. The maximum excess gas temperature is found to be 1350 °C.

1. Introduction

The stability of the tunnel structure is a key design parameter when concerning the fire safety design of tunnels. For example a tunnel may be the key transportation line between two countries as in the case of the Mont Blanc fire or the St:Gotthard tunnel fire [1]. A large fire can jeopardize the tunnel construction if the fire becomes too intense over a long period of time. Our knowledge concerning the impact of thermal exposure of the fire on the tunnel construction and how to calculate the stability of the structure is, therefore, critical. Traditionally, heat exposure to a tunnel construction is based on the use of standardized time–temperature curves. Indeed, standard fire temperature curve such as ISO 834 [2], the Hydrocarbon Curve (HC) [3] or the RWS curve [4] are widely used to test the tunnel linings, see Fig. 1.

Other time–temperature curves that are used in specific applications include RABT/ZTV [5], HCM [6] and EBA [7]. All these curves are derived in different ways and usually based on large scale or small scale tests or by consensus of technical committees working nationally or internationally in this field. When choosing different curves, there is no single guideline document concerning how to choose one curve in relation to the heat release rates, longitudinal ventilation velocity or the ceiling heights compared to others.

Traditionally, tunnel engineers use these standardized time–temperature curves to design the load bearing system of the tunnel construction. The system is designed from these arbitrarily chosen standardized time–temperature curves which are used as input for calculation of the temperature distribution inside the structure. The temperature is converted into heat flux towards the construction and the temperature inside the construction is calculated as a function of the distance from the outer surface of the construction. In the case of a concrete tunnel construction, the temperatures in the reinforced steel bars are calculated. When the temperature reaches a certain critical value the time to collapse is determined. This method is accepted by most authorities around the world and means that the analysis will be critically dependent on the choice of the time–temperature curve.

The method is crude and prescriptive and therefore not applicable for performance based design. Due to this fact, there is a need to develop a reliable engineering tool based on theoretical analysis that can predict the gas temperature as a function of the tunnel geometry, heat release rate and ventilation conditions. Earlier studies, like the one carried out by Kurioka et al. [8] proposed an empirical equation to predict the maximum gas temperature rise below the tunnel ceiling and its position relative to the center of the fire. Hu et al. [9] compared Kurioka's equation with their full-scale data and showed that there was a good agreement. However, the heat release rates of Hu's full-scale tests [9] were too small compared to the tunnel geometry. In the equation given by Kurioka et. al., the maximum gas temperature rise below the ceiling approaches infinite, when the ventilation velocity approaches zero. The consequence will be that the maximum gas temperature rise below the ceiling cannot be predicted correctly when the ventilation velocity is very low. Further, the maximum gas temperatures from Kurioka's experiments tends to be high, as the tunnel ceilings were lined with thick fireproof blankets, similar to adiabatic boundaries, which

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Nomenclature

a	Thermal diffusivity (m^2/s)
A	contact area for heat conduction (m^2)
b_{fo}	radius of the fire source (m)
c_p	heat capacity of air (kJ/kg K)
c_s	heat capacity of a specific material (kJ/kg K)
C_T	temperature correction coefficient defined in Eq. (1)
DTR1	Delta T in Region I defined in Eq. (12)
DTR2	Delta T in Region II defined in Eq. (13)
g	gravity acceleration (m/s^2)
h	total heat transfer coefficient (kW/m^2 K)
H_{ef}	vertical distance between fire source bottom and tunnel ceiling (m)
k_s	thermal conductivity (kW/m K)
m_p	mass flow rate of the fire plume at the ceiling height (kg/s)
M_p	mass of the control volume (kg)
Q	total heat release rate (kW)
Q_c	convective heat release rate (kW)
q''_{cond}	heat flux by conduction (kW/m^2)
Q_{cond}	heat loss by conduction (kW)
t	time (s)
t'	time (min)
t_p	thermal penetration time (s)
T_o	ambient temperature (K)
T	gas temperature (K)
$T_{\max}$	maximum ceiling temperature (K)
T_w	wall temperature (K)
ΔT	excess gas temperature (K)
$\Delta T_{\max}$	maximum excess temperature beneath the ceiling (K)
V	longitudinal ventilation velocity (m/s)
V'	dimensionless ventilation velocity

Greek symbols

ρ_a	ambient density (kg/m^3)
ρ_s	density of a specific material (kg/m^3)
δ	thermal penetration depth (m)
χ_r	fraction of radiative heat release rate

could underestimate the heat loss near the fire sources. The consequence may be that the maximum gas temperature rise under the tunnel ceilings will be overestimated. Moreover, the proposed correlation was originally obtained by empirical correlations rather than theoretical analysis.

Li et al. conducted a theoretical analysis of the maximum gas temperature rise below the ceiling based on an axisymmetric fire plume theory [10]. The necessary empirical coefficients were obtained from experimental data. The proposed formulae for the maximum excess gas temperature beneath the ceiling fit the data from both model scale tests and large scale tests. A comparison of the proposed formulae with the Kurioka's equation was also made. The results showed that the formulae proposed by Li are better able to predict the maximum gas temperature, especially when the ventilation velocity is very small. However, the proposed formulae may not be valid if the heat release rate is so large that the combustion zone reaches up to the tunnel ceiling. If this occurs, the maximum gas temperature was expected to be a constant independent of the heat release rate, ventilation velocity and tunnel height.

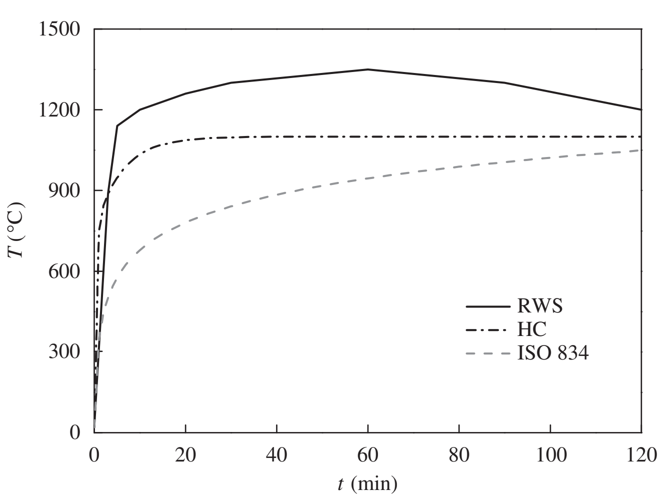

Fig 1. The most common standardized time-temperature curves for road tunnel applications.

In the present paper, the theory of the plume mass flow rate and maximum temperature beneath the ceiling for a small fire in a tunnel as given by Li et al. [10] is further developed. For a large fire in a tunnel, the parameters influencing the maximum temperature are analyzed, according to theoretical considerations and tests data. Different ventilation systems, heat release rate, ventilation velocity, geometry of the tunnel and fire source are all taken into account. The theoretical analysis provides the basis for an engineering model to calculate the maximum gas temperature depending on the relevant parameters listed above. Data from numerous model scale and large scale tests have been used in the analysis.

2. Theoretical considerations

2.1. Small fire

According to the previous theoretical study concerning the maximum excess gas temperature beneath the tunnel ceiling by Li et al. [10], the maximum excess gas temperature beneath the ceiling in a tunnel fire can be expressed as

$$\Delta T_{\max} = \begin{cases} 14.1 C_T (1-\chi_r)^{2/3} \dfrac{Q^{2/3}}{H_{ef}^{5/3}}, & V' \le 0.19 \\ \dfrac{2.68 C_T (1-\chi_r)^{2/3} g^{1/3}}{(\rho_o c_p T_o)^{1/3}} \dfrac{Q}{V b_{fo}^{1/3} H_{ef}^{5/3}}, & V' > 0.19 \end{cases} \quad (1)$$

where

$$V' = V \bigg/ \left(\frac{gQ}{b_{fo} \rho_o c_p T_o} \right)^{1/3}$$

In Eq. (1), H_{ef} is the effective tunnel height, i.e. the vertical distance between the bottom of the fire source and the tunnel ceiling, see Fig. 2.

Since Eq. (1) is obtained based on the assumption that the flow profile and the gas temperature profile across the section of the fire plume at any height follows a top-hat profile, the temperature correction coefficient, C_T, defined in Eq. (1), has to be determined by experimental data. Based on the experimental data, the following