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Experimental analysis of the influence of accumulated upper hot layer on the maximum ceiling gas temperature by a modified virtual source origin concept

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ABSTRACT

This paper presents an experimental investigation to explore the influence of an accumulated hot upper layer on the maximum ceiling gas temperature of buoyancy-driven thermal flow in a reduced scale tunnel model. Experimental results show that the maximum excess temperature changes small with the decreasing of distance between fire source and the nearest sidewall until fire is flush with sidewall, then the maximum ceiling gas temperature increases significantly. A modified concept of virtual origin is introduced for calculating the maximum ceiling gas temperature in the presence of a hot upper layer beneath ceiling. On the basis of the experimental data and theoretical analysis, correlations of the virtual source location are proposed for fire placed out of touch and flush with sidewall, respectively. Further, the predicted maximum ceiling gas temperatures are compared with the measured ones for fire out of touch with sidewall as well as the data from other model-scale and full-scale tests. The results show that there is a good agreement when the modified dimensionless heat release rate, $\dot{Q}_{\text{mod}}$, which expresses the relative size of heat release rate compared to the tunnel geometry, is smaller than 0.09, otherwise the predicted maximum temperatures will be lower than the experimental values because of the impingement of intermittent flame on the tunnel ceiling.

1. Introduction

In recent years, a number of high profile accidental fires have occurred in numerous road and rail tunnels throughout the world. Many of these fires grew rapidly and caused tremendous deaths and injuries and severe damage to the tunnel structures, such as the Viamala Tunnel Fire in 2006, killing 9 people [1], the St. Gotthard tunnel fire in 2001, killing 11 people and the Mont Blanc tunnel fire in 1999, killing 41 people [2], etc. In case of a tunnel fire, the characteristics of buoyancy-driven thermal flow, including the ceiling gas temperature, distribution of hazardous combustion products, the critical ventilation velocity and back-layering length are important issues in evaluation its hazard degree [3–8]. Due to the special narrow and long structure of tunnel, the high temperature smoke and heat are difficult to be discharged timely and then accumulate beneath the ceiling, which has a quite strong risk to the stability of the tunnel structure. Once the steel bars in the concrete are exposed to the hot smoke over a certain period of time, the strength of them will descend evidently, eventually causing the collapse of tunnel structure. Therefore, in order to provide adequate fire protection for tunnel structure and properly design the fire detectors, the maximum gas temperature beneath the tunnel ceiling to which the structure is exposed needs to be estimated.

Alpert [9] provided a simple correlation for predicting the maximum ceiling gas temperature, where the distances between fire and the nearest vertical wall should be not less than 1.8 times of the ceiling height. The equation is given by

$$\Delta T_{\max} = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}} \tag{1}$$

where H is the ceiling height, $\dot{Q}$ is the heat release rate. Ji et al. [10] has conducted a series of experiments in a model-scale subway station and demonstrated the validity of Alpert's equation for determining the maximum ceiling gas temperature in the presence of hot upper layer. In their experimental conditions, the distance between fire and the nearest sidewall is only 1.25 times of the ceiling height. Considering the special narrow and long structure of tunnel, the requirement of Alpert's equation could not be met even for fire at the longitudinal centerline. Therefore, the validity of

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Nomenclature

ΔT_{max}	maximum excess gas temperature beneath the ceiling
ΔT_0	plume centerline temperature
g	gravity acceleration
H	ceiling height
H_{ef}	vertical distance between fire source bottom and ceiling
d	distance between fire source and the nearest sidewall
T_a	ambient temperature
c_p	specific heat capacity
b	radius of the fire source
z_0	virtual origin height
D	equivalent diameter of fire source
$\dot{Q}$	heat release rate
$\dot{Q}_{mod}$	modified dimensionless heat release rate
$\dot{Q}_c$	the convective heat release rate
V	longitudinal wind speed
L_f	mean flame height

Greek letters

ρ_a	density of ambient air

Superscripts and subscripts

f	full scale
m	model scale

Alpert's equation should be experimentally validated, especially for fire close to the sidewall.

Kurioka et al. [11] proposed a model to predict the maximum smoke temperature beneath the tunnel ceiling based on the experiments in a model-scale longitudinal ventilated tunnel. Nonetheless, as Li et al. [12] pointed out, the equation by Kurioka cannot predict the maximum ceiling temperature correctly in case of low ventilation velocity. And they put forward a more applicable equation for relatively low ventilation flows, which is given by,

$$\Delta T_{max} = 17.5\frac{\dot{Q}^{2/3}}{H_{ef}^{5/3}}, \quad V' = V\Big/\left(\frac{g\dot{Q}}{b\rho_a c_p T_a}\right)^{1/3} \leqslant 0.19 \tag{2}$$

where $\dot{Q}$, b, H_{ef} and V are the heat release rate, radius of the fire source, vertical distance between fire source bottom and ceiling and the longitudinal wind velocity in tunnel, respectively.

A review of the state of the art reveals that although a number of correlations exist for the prediction of the maximum ceiling gas temperature, however, in the former studies fire sources are always located at the longitudinal centerline of tunnel [5,6,11,12], as a matter of fact fire occurs at any transverse locations and the nearby sidewall will influence the ceiling gas temperature more or less. Due to this fact, there is a need to develop a reliable engineering tool based on theoretical analysis that can predict the maximum ceiling gas temperature more realistically, taking the tunnel geometry, heat release rate and transverse fire location into consideration.

2. Experimental procedure

The experiments were conducted in a model-scale tunnel with scale ratio of 1:6. The model tunnel is 6 m long, 2 m wide and 0.88 m high (see Fig. 1). As shown in Fig. 1, the side near the aisle was made up of 6 mm thick fire-resistant glass to observe the experimental phenomena, the top, bottom and the other side of tunnel were 8 mm thick fireproof board. Its aspect ratio is determined based on a survey of 17 urban road tunnels in Beijing, Nanjing and Shenzhen in China, and is considered to be an extensive representation. The idea of applying similar model to fire research was first proposed by Thomas [13], after the development and improvement of the later scholars [14,15], the approach of physical scale modeling has evolved into an effective way to study the phenomenon of fire and smoke [5–8]. To ensure that the results can be extrapolated to full scale, Froude modeling was applied with the requirements for the equivalent flows fully turbulent on both full and model scale [13]. The previous work by us has confirmed that the smoke flow inside this model-scale tunnel is indeed fully turbulent with Reynolds number larger than 4000 [6]. The dimensional relationships between the fluid dynamics variables were derived from first principles by Morgan et al. [16]. By holding the Froude number constant, the scaling of the temperature and heat release rate between full and model scale are given by $T_m = T_f$ and $\dot{Q}_m/\dot{Q}_f = (l_m/l_f)^{5/2}$, where $\dot{Q}$ is the heat release rate (HRR), l denotes the size and l_m/l_f is the similarity ratio. The subscript 'm' and 'f' represent the model and full scale parameters, respectively.

Fig. 1. Photograph of the experimental apparatus.

A total of 63 pool fire tests were conducted with methyl alcohol employed as fuel, each test was conducted two times to ensure reproducible results within permitted error ranges. The oil pool was placed on the floor with different distances to the fireproof sidewall, and the distances were 1, 0.75, 0.5, 0.4, 0.3, 0.2 and 0 m respectively.

The burning rate of methyl alcohol pool fire in the experiments is fuel-controlled based on the semi-empirical equation proposed by Harmathy [17]. That is, the burning rate under the experimental conditions depends predominantly on the surface area of the oil pools and the air supply is ample. Yi et al. [18] pointed out that, with adequate air supply, combustion of methanol in the tunnel is similar to that in free space. Therefore, in this research the burning rate determined by an electronic balance in open space is adopted and the heat release rates (HRR) are 3.38, 4.93, 6.95, 9.44, 12.56, 16.45, 20.21, 23.80 and 29.57 kW, respectively. The HRRs are in the range of 3.38 to 29.57 kW, with the corresponding values in full scale between 0.30 MW to 2.61 MW.

A data acquisition system (Agilent 34980A) was used for the temperature measurements and its sampling interval was set to be 2 s. Gas temperature beneath the ceiling was measured by K-type stainless steel-sheathed thermocouples with a diameter of