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Determination of smoke layer interface height of medium scale tunnel fire scenarios

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ABSTRACT

Smoke layer interface height is an important parameter in fire safety science. In this paper, a series of experiments were conducted in a 1/6th scale model tunnel for determining the smoke layer interface height in medium scale tunnel fire scenarios. The commonly used approaches, including visual observation, *N*-percentage rule and integral method are reviewed firstly. Then, considering the subjectivity and empiricism of previous approaches, a buoyancy frequency method is put forward based on the vertical temperature distribution in tunnel, which has definite physical meaning and eliminates the subjectivity of previous methods. The smoke layer thicknesses determined by buoyancy frequency method are compared with the results of visual observation, *N*-percentage rule ($N = 10$, 20, 30) and integral ratio method, respectively. The comparison results reveal that the smoke layer thicknesses determined by buoyancy frequency method fit best with the visual values for all the experimental conditions. While the calculated values by integral ratio method are lower than the visual values. In addition, the selection of optimum *N* values for the *N*-percentage rule in different cases is also discussed.

1. Introduction

Statistics have shown that smoke, including both the particulate and gaseous components of the combustion products, is the most fatal factor in fires, and about 85% of victims are killed by the hot and toxic smoke (Beard, 2009). Owing to the hazardous effects of smoke, the determination of smoke layer interface in case of a fire is a subject of great interest in the field of fire safety science.

Cooper et al. (1982) proposed a *N*-percentage rule to determine the smoke layer interface height based on the experiments of multi-room fires and stated that the 10% rule (i.e. $N = 10$) would provide a reasonable result. However, different researchers used discrepant *N* values for various fire scenarios (Chow, 2009; He et al., 1998; Tilley et al., 2011; Zhang et al., 2012) and the selection of *N* value is subjective and empirical. Chow (2009) and Emmons (1989) estimated the smoke layer interface as the position with sharp changes of vertical temperature. When the temperature gradient in the vicinity of smoke–air interface is small, the accuracy of this method will decrease a lot. In order to eliminate the subjectivity and empiricism of the previous methods, He et al. (1998) put forward an integral ratio method and a least-squares method to determine the smoke layer interface height based on the mathematical process to divide the vertical temperature into two relatively uniform regions. Yet their experimental results of a real building corridor fire showed that the interface heights determined by these two methods tended to yield higher values.

Therefore, in view of the limitations of the existing approaches, a buoyancy frequency method, based on the vertical density stratification, was put forward to determine the location of smoke layer interface. A set of experiments were conducted in a 1/6th scale model tunnel to validate the applicability of different methods in medium scale tunnel fire scenarios.

2. Determination of smoke layer interface height

2.1. Visual observation

In model scale experiments, it is easy and convenient to read the smoke layer interface height by a vertical scale. The interface height obtained by visual observation is based on the difference of vertical density and visibility, which directly reflects the smoke layer stratification. However, for clean fuels, e.g. methanol, methane,

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Nomenclature

T	temperature (°C, K)
g	Gravity acceleration (m/s^2)
N	value in the N-percentage rule
N_L	value of buoyancy frequency (s^{-1})
H	ceiling height (m)
r	integral ratio
t	time (s)
z	vertical height (m)

Greek letters

ρ	density (kg/m^3)

Subscript

i	interface
amb	ambient
max	maximum
u	upper layer
l	lower layer
lo	local
min	lowest

hydrogen, etc., very little soot is produced, the smoke layer is hardly visible and it will be difficult to read the interface visually.

Moreover, in real fire scenarios, smoke is highly toxic and the large amount of black smoke hinders the video recording, causing the approach of visual observation inapplicable.

2.2. N-percentage rule

The N-percentage rule, proposed by Cooper et al. (1982), is a simple method to locate the vertical position with sharp changes of temperature and regard it as the smoke layer interface of a fire scenario. This method has been used in many different scenarios, including the model-scale and full-scale structures with height ranging from 0.8 m to 32.8 m (Chow, 2009; He et al., 1998; Tilley et al., 2011; Zhang et al., 2012). This empirical rule determines the interface as being the height where the temperature rising over the ambient temperature is equal to N % of the maximum rise over the ambient temperature. The interface height can be quantified as:

$$T_i - T_{amb} = (T_{\max} - T_{amb}) \times N/100 \tag{1}$$

where T_i is temperature at interface height, T_{amb} is the ambient temperature, $T_{\max}$ is the maximum temperature in vertical direction. By adopting N-percentage rule, the interface height is assumed a monotonic decreasing function in time, which may limit its application (He et al., 1998).

However, although the N-percentage rule is widely used by previous researchers for various building structures, such as tunnel, atrium, and multiroom, the selecting of N value is often confusing, the adopted N values not consistent with each other and the most commonly used ones are 10, 20 and 30 (see Table 1). Thus, the N-percentage rule for different N values together with other methods are adopted to synthetically estimate the most appropriate method for the specific tunnel fire scenarios.

2.3. Integral ratio method

The integral ratio method was proposed by He et al. (1998). It divided the temperature profile into two separate regions so that the averaged bi-valued distribution gave the closest representation of the original distribution. The interface height can be calculated by

$$r = r_u + r_l = \frac{1}{(H-H_i)^2}\int_{H_i}^{H} T(z)dy \int_{H_i}^{H} \frac{1}{T(z)}dy + \frac{1}{H_i^2}\int_0^{H_i} T(z)dy \int_0^{H_i} \frac{1}{T(z)}dy \tag{2}$$

$$r(H_i) = \min(r_t) \tag{3}$$

where H is the ceiling height, H_i is the interface height, $T(z)$ is the function of temperature, r is the integral ratio. The subscripts "u" and "l" denote upper layer and lower layer, respectively.

For a given temperature distribution $T(z)$ over the region $[0, H]$, the interface height H_i is defined as the value of H at which r attains the minimum value. As shown in Eq. (2), this method does not rely on any external reference parameter as N-percentage rule. Nonetheless, the integral ratio method tends to yield higher values of the interface height by comparing with full scale experimental data (He et al., 1998). Hence, this may give unduly optimistic fire risk estimation when it comes to personnel evacuation terms.

2.4. Buoyancy frequency method

Considering the limitation and applicability of the existing methods, a buoyancy frequency method, is put forward in this paper to obtain more accurate estimation of the smoke layer interface height and reduce the subjectivity and error of the above approaches.

Buoyancy frequency is one of a basic parameter of heterogeneous flows and it is previously used in atmospheric dynamics, oceanography, and geophysics (Mcdougall et al., 1988; Gill, 1982; Davey and Reid, 1977; McHugh, 2015). Consider first the motion of an element of inviscid fluid displace a small distance η vertically from its equilibrium position in a stable environment, based on the linearized Boussinesq equations for an inviscid liquid, η gives (Turner, 1973),

$$\frac{\partial^2 \eta}{\partial t^2} = \frac{g \partial \rho_{amb}}{\partial z}\eta \tag{4}$$

The element will thus oscillate in simple harmonic motion with angular frequency,

$$N_L = \left(-g\frac{\partial \rho_{lo}}{\partial z}\Big/\rho_{amb}\right)^{1/2} \tag{5}$$

The fire plume can be always considered as the ideal gas ($\rho_{lo} = T_{amb}\rho_{amb}/T_{lo}$) (Quintiere, 2006), then N_L becomes,

$$N_L = \left(-gT_{amb}\frac{\partial(1/T_{lo})}{\partial z}\right)^{1/2} \tag{6}$$

where N_L is the value of buoyancy frequency in vertical direction, ρ_{lo} is the local density in vertical direction, ρ_{amb} is the density of

Table 1
Adopted N values by previous researchers.

Reference	N value	Fire scenario	Research methods
Cooper et al. (1982)	10	Multiroom	Full scale experiments
Chow (2009)	10/15/20	Atrium	Full scale experiments
He et al. (1998)	15	Multiroom	Full scale experiments
Tilley et al. (2011)	30	Atrium	Numerical simulations
Zhang et al. (2012)	10	Tunnel	Small scale experiments