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Maximum gas temperature rise beneath the ceiling in a portals-sealed tunnel fire

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ABSTRACT

Sealing tunnel portals is an important approach to control tunnel fires. The maximum gas temperature rise beneath the ceiling was studied under the effects of both fire location and size in a portals-sealed tunnel model. Previous studies showed that the maximum gas temperature rise decreases when fire source is away from the tunnel center, companied with increasing flame inclination angle. In this study, based on dimensional analysis, an empirical model was developed to predict the maximum gas temperature rise beneath the ceiling in a portals-sealed tunnel. It is known that this model can provide reasonably good predictions to different fire scenarios considering fire location and size. A 3/4-power relationship was shown between maximum gas temperature rise and dimensionless fire size, while the normalized maximum gas temperature rise follows an attenuation law of $e^{-\varphi}$ with the fire location. The focus of the study is more of an academic nature than practical. This is an academic study with pioneering character, which in future may be solved in a more practical way than presented here. However, the outcomes from this study can provide a better understanding for the fire behavior in the portals-sealed tunnel fires and credible prediction about maximum gas temperature under related fire scenarios.

1. Introduction

Traffic tunnels, such as road tunnel, railway tunnel and subway tunnel, have been built rapidly and widely around the world in the past few decades. They plays an important role in modern transportation system (Yi et al., 2013), which provides a great alternative to release the heavy traffic pressure and promote freight transport under the promptly growing population (Fan and Yang, 2017). Companied with the conveniences, however, the increasing number of tunnels has brought many accidents, especially for those catastrophic fire accidents (Chen et al., 2016; Harish and Venkatasubbaiah, 2014; Li and Ingason, 2016). Due to their special long-narrow building-structures, tunnel fires can become catastrophic with a large amount of casualties, economic losses and social impacts (Lee et al., 2016; Li et al., 2016; Meng et al., 2014; Zhong et al., 2013). Hence, the study on tunnel fire control with aiming to reduce the release of energy has become a priority for the government departments and relevant authorities.

For road tunnel fire, longitudinal ventilation and transverse exhaust are usually utilized to prevent smoke spreading and then create a non-smoke space for evacuees and fire-fighters (Fan et al., 2017a; Ingason and Li, 2010, 2011). Besides, several fire-fighting systems, such as water spray, are also equipped inside the road tunnels to reduce the risk of fire propagation (Ingason et al., 2014). However, heavy haul railway tunnels are usually away from the city. Especially for those regional tunnels, the fire service intervention is relatively limited, with the critical needs of improving the fire safety and control measures. Under the event of a heavy haul railway tunnel fire, the generated toxic smoke gases spread fast and widely, which prohibits firefighters from entering the tunnel for fire suppression (Hu et al., 2007; Ji et al., 2013). Under this condition, sealing tunnel portals is an important approach to control tunnel fires (Chen et al., 2017; Yao et al., 2018a), which can be achieved by blocking the two tunnel portals with sand bags to prevent fresh air supply from outside. Sealing tunnel portals can be carried out after all the passengers succeed to evacuate. Similar fire scenarios can also appear in a building corridor, cable tunnel, mine tunnels and tunnels under construction. After the sealing, the fire can be controlled over a period of time because of the occurrence of vitiation, where the oxygen is inerted by combustion gases such as vapour and CO_2. The fire behavior within the portals-sealed tunnel, which is different from the regular tunnel fire, is of a paramount importance to the fire control.

It should be pointed out that the actual application of sealing tunnel portals in a tunnel fire is very complex due to a large amount of uncertain factors. Firstly, after the tunnel fire, the portals may not be sealed immediately due to external factors. Secondly, the tunnel portals

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Nomenclature

Abbreviations

c_p	specific heat capacity of ambient air (kJ/kg K)
ρ_0	ambient air density (kg/m^3)
g	gravity acceleration (m/s^2)
T_0	ambient air temperature (K)
V	longitudinal ventilation velocity (m/s)
$\Delta T_{\max}$	maximum gas temperature rise underneath tunnel ceiling (K)
$\Delta T_{\max,0}$	maximum gas temperature rise when fire is located at the tunnel center (K)
$\Delta T_{\max,\varphi}$	maximum gas temperature rise considering the distance between fire location and tunnel center (K)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate (–)
d	longitudinal distance between fire source and tunnel center (m)
H_{ef}	effective tunnel height (m)
L	tunnel length (m)
φ	dimensionless distance between fire source and tunnel center (–) defined as $d/(L/2)$
α	coefficient shown in Eq. (1)
β	coefficient shown in Eq. (9)
Fr	Froude number (–)

are not always sealed completely because of the hot smoke and toxic gas beneath the ceiling at tunnel portals (Chen et al., 2017). However, from the perspective of academic work, the scenario with full sealing at both tunnel portals immediately after the fire occurrence was considered in this study. Therefore, the focus of the study is more of an academic nature than practical, which in future may be solved in a more practical way than presented here.

One of the biggest concerns for the applications of sealing tunnel portals in a tunnel fire is the fire duration and related maximum gas temperature rise beneath the ceiling before the fire can be actually controlled. It is because the related parameters are important to evaluate the impacts of the method on the tunnel structures. The prediction of the fire duration can be simply calculated by the amount of fuel and the volume of tunnel, while the maximum gas temperature rise is relatively complicated, especially under sealed conditions. This is because the portals-sealed tunnel can complicate the predictions of smoke movement and temperature. Moreover, the fire location can also differ the fire behaviors inside the tunnel.

Limited literatures have been found on addressing the flame behaviors and maximum gas temperature rise in a portals-sealed tunnel fire (Chen et al., 2017; Yao et al., 2017, 2018a). Previous study (Yao et al., 2017) has revealed that the flame in a portals-sealed tunnel tends to incline to the closer end wall with an increasing angle when the fire source is away from the tunnel center, while the maximum gas temperature rise then keeps decreasing all the time within a dimensionless distance ($d/(L/2)$) of 0–0.64. It was also known from the experiments that gas temperature and pressure on the two sides of the flame could be different when the fire source is not in the tunnel center. Our current effort is to put forward this research by quantifying the sealing effect and fire location on the maximum gas temperature rise beneath the ceiling.

Based on fire plume theory, Alpert (1972), Li et al. (2011) and Ji et al. (2012) developed one type of theoretical models to predict the maximum gas temperature rise beneath the ceiling for tunnels without or with limited ventilation. Their models can be expressed by Eq. (1) with a range of coefficient α between 16.9 and 17.9, which is probably because of the different aspect ratios of tunnels and tested fuels and testing methods:

$$\Delta T_{\max} = \alpha \frac{\dot{Q}^{2/3}}{H_{ef}^{5/3}} = [\alpha(\rho_0 T_0 c_p)^{2/3} g^{1/3}]\dot{Q}^{*2/3} \tag{1}$$

with

$$\dot{Q}^* = \dot{Q}/\rho_0 T_0 c_p g^{1/2} H_{ef}{}^{5/2} \tag{2}$$

where $\dot{Q}$, H_{ef}, ρ_0, T_0, c_p, g, $\dot{Q}^*$ are the heat release rate, effective tunnel height, ambient air density, ambient air temperature, specific heat capacity of air, gravity acceleration and dimensionless heat release rate, respectively.

Gao et al. (2014) proposed an empirical model to predict maximum ceiling temperature rise under natural ventilation by experiments in a 1/6 reduced scale urban road tunnel model:

$$\Delta T_{\max} = 1000\dot{Q}^{*1/2}, \quad \dot{Q}^* < 0.04 \tag{3}$$

Kurioka et al. (2003) proposed another empirical model to predict the maximum temperature rise of smoke layer by both reduced-scale and full-scale tunnel experiments. Through this model, the maximum gas temperature rise beneath the ceiling approaches infinity when the longitudinal ventilation velocity approaches zero, which means that it is not fully applicable to those limited ventilation conditions:

$$\frac{\Delta T_{\max}}{T_0} = 1.77\left(\frac{\dot{Q}^{*2/3}}{Fr^{1/3}}\right)^{6/5} = 1.77\frac{\dot{Q}^{*4/5}}{Fr^{2/5}}, \quad \dot{Q}^{*2/3}/Fr^{1/3} < 1.35 \tag{4}$$

where Fr is the Froude number and defined by:

$$Fr = V^2/gH_{ef} \tag{5}$$

where V is the longitudinal ventilation velocity.

Through this study, based on previous experimental results (Yao et al., 2017) and dimensional analysis, a new empirical model was proposed to predict the maximum gas temperature rise beneath the in a portals-sealed tunnel ceiling considering fire locations and sizes. In addition, the sealing effects on tunnel fire were also addressed by comparing our predictions with previous models (Alpert, 1972; Gao et al., 2014; Ji et al., 2012; Li et al., 2011).

2. Dimensional analysis

Based on previous studies (Alpert, 1972; Gao et al., 2014; Ji et al., 2012; Kurioka et al., 2003; Li et al., 2011), it is known that the determining parameters for maximum gas temperature rise beneath the ceiling under tunnel fires include the heat release rate, ambient air temperature, ambient air density, specific heat capacity of air, gravitation acceleration and effective tunnel height. However, when a fire occurs in a portals-sealed tunnel, except for above parameters, the longitudinal fire location was found to have a significant influence on the maximum gas temperature rise (Yao et al., 2017). The fire location can be characterized by the dimensionless distance between fire source and tunnel center (defined as the ratio of fire source-tunnel center distance and half of tunnel length, i.e. φ). Consequently, the maximum gas temperature rise beneath the ceiling in a portals-sealed tunnel fire can be expressed by:

$$\Delta T_{\max,\varphi} = (\dot{Q}, \quad T_0, \quad \rho_0, \quad c_p, \quad g, \quad H_{ef}, \quad \varphi) \tag{6}$$

Based on dimensional analysis, T_0, ρ_0, g and H_{ef} are selected as the independent variables, and then Eq. (6) can be rearranged as:

$$\frac{\Delta T_{\max,\varphi}}{T_0} = f\left(\frac{\dot{Q}}{H_{ef}^{7/2}\rho_0 g^{3/2}}, \quad \frac{c_p T_0}{H_{ef} g}, \quad \varphi\right) \tag{7}$$

By multiplying the first term and the reciprocal of the second term on the right-hand side of Eq. (7), the dimensionless heat release rate can