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A computational study on effects of fire location on smoke movement in a road tunnel

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ABSTRACT

In this work, a numerical model of tunnel fire is developed and aimed to investigate the influence of cross-sectional fire locations on critical velocity and smoke flow characteristic. It is shown that the critical velocity for a fire next to the wall is obviously higher than that for a fire in the middle or on the left/right lane. The ratio is estimated to be 1.12. The predictions of critical velocity from 'small-fire' models show a good agreement with that for a fire in the middle or on the left/right lane from CFD. The tunnel height at the fire location is proposed to be instead of the hydraulic tunnel height in the 'big-fire' model of Wu and Bakar for a fire next to the wall. The smoke moves backward in a tongue like form as the ventilation velocity is lower than the critical velocity. The back-layering length of a fire in the middle is shown to be approximate twice than that on the left/right lane under the same ventilation velocity, although they share the same critical velocity. Whereas a relatively short back-layering length for a fire next to the wall under the velocity of 2.6 and 2.7 m/s. In addition, a snaky high-temperature profile on the top wall at the initial downstream is observed for a fire on the left lane and next to the wall, and finally a steady and layered smoke flow. The likely cause of this phenomenon is subsequently explained in this study.

1. Introduction

Several catastrophic road tunnel fires over the past two decades have brought significant losses of life and severe destruction to tunnel structure. Such as Mont Blanc tunnel fire between France and Italy in 1999, causing 39 deaths and the tunnel closed for 3 years. Tauern tunnel fire in Austria in 1999, causing 12 deaths and the tunnel closed for 3 months. Gotthard tunnel in Switzerland in 2001, causing 11 deaths (Lonnermark, 2005). These catastrophes stress a need for special care to road tunnel fire safety and accordingly attract much attentions from international research community. Some following projects are launched to investigate the road tunnel fire science, such as EUREKA project where nine European nations cooperated, FIT project and UPTUN project (Haack, 1998; FIT, 2003; Hejny, 2005). These projects have prominently improved our understanding of the road tunnel fire.

Tunnel fire, however, is a very complex phenomenon because of the mutual interactions between fire dynamic process (for example turbulence, combustion, radiation, etc.) and tunnel geometry layout (such as tunnel geometry, vehicle geometry and their layout). From these occurred road tunnel fires, the causes of tunnel fire can be classified into vehicle self-ignition (including load, fuel and vehicle), and vehicle collision and over-turning (for instance the front-back collision and collision with side wall). These causes of road tunnel fire would make the possibility of the random layout of fire in a tunnel, such as a fire next to the wall, on the left/right lane, or in the middle. Furthermore, the fire development, the smoke dispersion and the damage to tunnel lining are strongly dependent on the fire location in a tunnel. Consequently, there is clearly a need for understanding smoke movement and tunnel fire safety management under these situations.

Tunnel longitudinal ventilation system is commonly provided in road tunnels to force a smoke flow in a designated direction. When the air speed is too low, fire smoke spreads toward both the upstream and the downstream. Nevertheless a higher-speed airflow would make the downstream full of fire smoke rapidly. Both of the circumstances might be dangerous for the evacuation and the fire fighters approaching the fire source. When the smoke back-layering is just disappeared, the corresponding longitudinal ventilation velocity is considered as the critical velocity. Accordingly, the critical velocity is one of the key criteria for the tunnel fire safety management system.

Studies of critical velocity have been undertaken by a number of researchers over the last few decades. Thomas firstly proposed a correlation of the critical velocity based on Froude number in a

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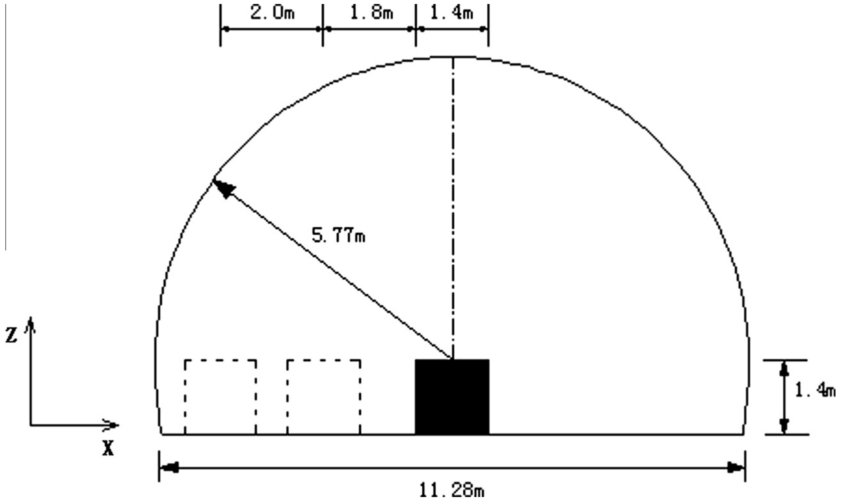

Fig. 1. Cross-section of the tunnel.

Table 1
The mesh description.

Mesh type	Longitudinal mesh size near fire (m)	Mesh size on the cross-section (m)	Total cells
A	0.1	0.12	3,264,762
B		0.15	2,015,853
C		0.2	1,167,327

tunnel fire (Thomas, 1958). Subsequently, Danziger and Kennedy introduced a critical Richardson number into the same mathematical expression (Danziger and Kennedy, 1982). After then, another group of similar expressions of critical velocity were provided by Oka and Atkinson (1995), Wu and Bakar (2000) and Li et al. (2010) through a series of small-scale experiments. Their expressions showed different effects of heat release rate on the critical velocity and exhibited a constant critical velocity value for a 'big fire'. Furthermore, Wu and Bakar introduced a hydraulic diameter into their model. Another critical velocity model was provided by Kunsch (2002). The maximum plume temperature overshooting the ambient at the tunnel ceiling was employed in his model.

However, it is noted that these models were reported to overshoot or undershoot some experimental results (Vauquelin, 2005). And thus some detailed studies of effects of tunnel shape, tunnel slope, tunnel blockage, etc., on the smoke movement and the critical velocity have been conducted. Lee and Ryou studied the effect of the tunnel cross-section aspect ratio on the critical velocity (Lee and Ryou, 2006). They found that the growth and development of smoke were affected by the aspect ratio as well as the heat release rate, and the critical velocity accordingly increased with the increase of the aspect ratio. Chow et al. used a scaled model to study the smoke movement pattern in a tilted tunnel with various angles (Chow et al., 2010, 2015). They found the critical velocity for preventing back-layering for tilted tunnels are higher than the values required for horizontal tunnels. Lee and Tsai presented an experimental study of effect of vehicular blockage on the critical velocity (Lee and Tsai, 2012). Their results showed the critical velocity decreased with the increase of the vehicle blockage ratio for vehicles positioned upstream of fires. Effects of blockage in longitudinal ventilated tunnel fires is subsequently studied numerically by Gannouni and Maad (2015). In addition, road tunnel ventilation system has attracted much attentions in the case of tunnel fire. Vega et al. conducted a numerical study of a longitudinal ventilation system in Memorial tunnel fire (Vega et al., 2008). They employed FLUENT code to reproduce the whole experimental program. The numerical results showed a reasonably agreement with the experimental results. Betta et al. proposed a 'Banana' jet fan and an optimal pitch angle in tunnel

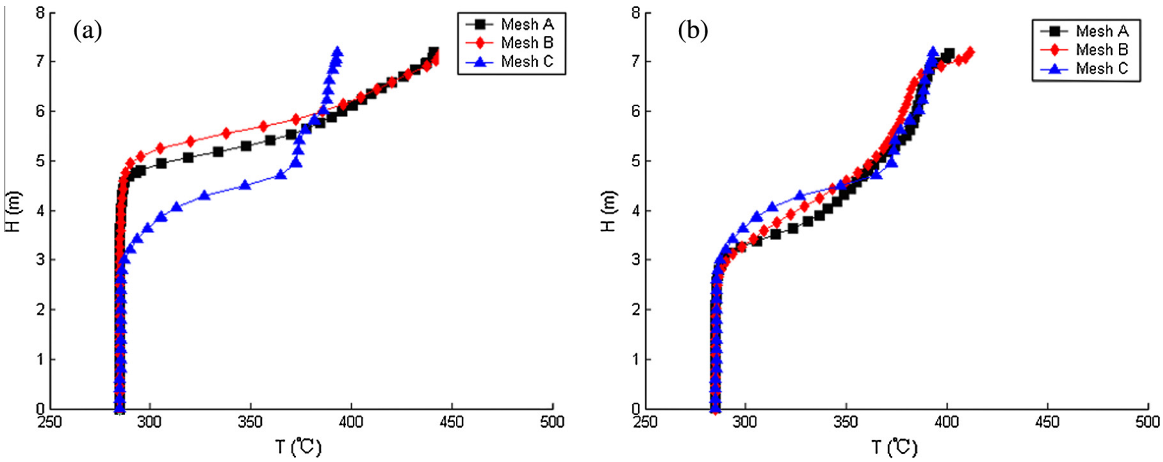

Fig. 2. Vertical temperature profiles at the downstream for three mesh sizes: (a) 15 m; (b) 30 m.