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The effect of fuel area size on behavior of fires in a reduced-scale single-track railway tunnel

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ABSTRACT

A set of experiments was carried out in a 1/9 reduced-scale single-track railway tunnel to investigate the effect of fuel area size on the temperature distribution and behavior of fires in a tunnel with natural ventilation. Methanol pool fires with four different fuel areas 0.6×0.3 m^2 (1 pan), 1.2×0.3 m^2 (2 pans), 2.4×0.3 m^2 (4 pans) and 3.6×0.3 m^2 (6 pans), were used in these experiments. Data were collected on temperatures, radiative heat flux and mass loss rates. The temperature distribution and smoke layer in the tunnel, along with overflow dimensions and radiant heat at the tunnel entrance were analyzed. The results show that as the fuel area enlarges, the fire gradually becomes ventilation-controlled and the ceiling temperature over the center of fire source declines. Burning at the central region of fire source is depressed due to lack of oxygen. This makes the temperature distribution along the tunnel ceiling change from a typical inverted V-shape to an M-shape. As observed in the experiments, a jet flame appeared at tunnel entrances and both the size and temperature of the flame increased with the enlargement of fuel area leading to a great threat to firefighters and evacuees in actual tunnel fires.

1. Introduction

Tunnel fires can lead to great casualties and economic losses (Carvel and Marlair, 2005; Carvel, 2012), e.g. the Simplon Railway Tunnel Fire of 2011, where 10 trucks filled with goods burned violently and the temperature reached 800 °C greatly reducing the structural integrity of the tunnel roof which was in danger of collapsing. Another fire was caused by two trucks filled with methanol crashing in a tunnel on the Jin Ji-Highway in China (March 1, 2014) causing 40 deaths and 12 injuries. Hence fire safety of tunnel has drawn much attention leading to a great number of studies targeting the delineation of fire characteristics in tunnels (Fan et al., 2013; Gehandler et al., 2014; Nilsen and Log, 2009).

A series of theories and models for the temperature and heat relate rate (HRR) of tunnel fire have been developed during the past few years based on CFD calculations and experimental results. Amouzandeh et al. (2014) and Migoya et al. (2009, 2011) conducted CFD simulations of fire in tunnel to predict the temperature distributions inside tunnel. Cheong et al. (2010) compared the estimation of HRR by the use of statistical approach and CFD approach considering the influences of ventilation conditions and tunnel geometry. Ingason (2005, 2009) and Ingason and Lonnermark (2005) developed a single mathematical expression for tunnel fires with different growth rates, and established a presentation of available design curves as well making fire design more convenient and reliable. Kurioka et al. (2003) exploited an empirical formulae for flame tilt, apparent flame height, the maximum temperature of the smoke layer and its position based on the results obtained in a 1/10 reduced-scale model tunnel. The above formulae were justified by Hu et al. (2006) and Wang et al. (2009) further with a series of fire experiments in actual tunnels, respectively. Kashef et al. (2013) and Yuan et al. (2013) investigated the ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation in reduced-scale tunnels, and also developed formulae to predict temperature distributions and extent of smoke diffusion.

On the other hand, experimental research on smoke movement and control of fire in tunnel has also been conducted by many researchers (Tong et al., 2009; Yoon et al., 2009; Chow et al., 2010; Ko and Hadjisophocleous, 2013; Meng et al., 2014). However, the temperature, smoke and other fire characteristics in tunnels can be influenced by various factors, and the specific factors have been investigated by some researchers. Hansen and Ingason (2012) and Hansen and Ingason (2011) studied the influence of fuel type on heat release rates and put forward simple theoretical calculations of the overall HRR of multiple objects. Lee and Tsai (2012) conducted small-scale experiments and numerical

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simulations to investigate the effects of vehicular blockage on tunnel fire behavior and critical ventilation velocity. Caliendo et al. (2013) studied the fire scenarios in different vehicle types with and without traffic in a bi-directional road tunnel. Guo and Zhang (2014) compared the analytical solution, experimental data and CFD simulation for longitudinal tunnel fire ventilation. Gannouni and Maad (2015) studied the effect of blockage on critical velocity and backlayering length in longitudinally ventilated tunnel fires. Ji et al. (2012, 2015a, 2015b, 2015c) investigated the impact of fire locations and aspect ratios of corridor-like structures on the maximum smoke temperature under the ceiling. Zhong et al. (2013a, 2013b) studied the fire smoke flow and natural ventilation with vertical shaft in tunnel at different longitudinal ventilation velocities. Chen et al. (2012, 2016) studied the effect of sealing on tunnel fire behavior. Li et al. (2011), Li and Ingason (2012), and Carvel et al. (2001) studied the influence of ventilation on ceiling temperatures and heat release rates. The above studies on different aspects and influence factors of tunnel fire provide the basis for later research. While these studies were carried out mainly using single fire sources and the fuel area is relatively small. When the scale of fire is large, the behavior of fire in tunnel may be thoroughly different. Thus, some scholars had paid attention to the research of tunnel fire with large fuel load, e.g. Beard (2006) proposed a theoretical model of major fire spread in tunnel and found that the critical rate of heat release for spread from an initial fire to a target Heavy Goods Vehicle (HGV) is predicted to be approximately between 30 and 40 MW at a ventilation velocity of 2 m/s. Further, Lönnermark and Ingason (2006) performed large-scale fire tests in the Runehamar tunnel in Norway to study critical distance for fire spread between HGV trailers for different heat release rates. Their valuable works have greatly improved the scientific understanding of tunnel fire with large fuel load, while special research on the influence of fuel area on the temperature distribution and behavior of fire in tunnel is relatively less, especially for the heavy haul railway tunnel where the fuel is always widespread while the train passing through with large amounts of goods. It is not known whether the temperature distribution presents the same trend when large area fuel burns or multiple fires occur simultaneously, e.g. the case that several compartments filled with liquid fuel catch fire at the same time as a freight train goes through a tunnel. However, this kind of fire often leads to huge casualties and serious damage to the tunnel structure. Therefore, it is necessary to study the influence of fuel area size on the characteristic and behavior of fires in tunnel.

In this paper, a series of experiments was conducted in a 1/9 reduced single-track railway tunnel with different fire source areas. Comparisons for characteristic of the fires with different fuel areas are conducted. Factors such as temperature, radiant heat and overflow flame etc. were considered to ascertain the effect of fuel area comprehensively. The study is expected to provide some references for the fire protection and fire fighting for tunnel.

2. Experimental configuration

2.1. Tunnel model

A series of experiments were performed in a 1/9 reduced arch-shaped tunnel. The tunnel was 8 m long and 0.6 m wide. The cross section was an arch with two vertical walls of 0.5 m and an arc segment of 0.3 m in height. Fig. 1 provides a view of the tunnel and Fig. 2 provides the three-dimensional layout of the tunnel structure. The vault was constructed from a steel frame wrapped with asbestos to ensure ruggedness and heat insulation, as shown in Fig. 1. The side-walls and tunnel bottom were constructed from bricks and concrete. Additionally, the side walls were plastered over with cement mortar to improve the airtightness. Six stone piers were built non-equidistantly (Fig. 4) near one of the entrances on which a thermocouple matrix was placed.

Fig. 1. General view of the reduced-scale tunnel.

Holes were installed at the bottom (Figs. 3 and 5) to contain electronic balances to measure fuel mass loss rate. These electronic balances were wrapped in asbestos and covered by fire-proof plates to avoid damage from high temperature. The location of these holes could be adjusted according to experimental conditions. Ignition holes were mounted in one side wall through which fuel was ignited. The size of the opening was 0.2 m × 0.2 m and the space between openings was 0.5 m. Once fuel was ignited, the openings were shut immediately.

Methanol (99% purity) was used as the fuel and loaded into steel pans (0.6 m × 0.3 m × 0.1 m) to simulate carriages filled with liquid fuels. Based on Froude number conservation, the scaling of the heat release rate, smoke temperature and smoke velocity between reduced-scale and full-scale follow the scaling laws (Ji et al., 2015d):

$$\frac{Q_m}{Q_f} = \left(\frac{L_m}{L_f}\right)^{5/2} \quad (1)$$

$$T_m = T_f \quad (2)$$

$$\frac{V_m}{V_f} = \left(\frac{L_m}{L_f}\right)^{1/2} \quad (3)$$

where, Q is the heat release rate (HRR), T is the temperature, V is the velocity, L denotes the model size and L_m/L_f is the similarity ratio. The subscript 'f' and 'm' represent the full and model scale parameters respectively.

The fire load is calculated based on the fuel mass loss measured in the experiments. The HRRs for the 4 different testing cases are 66.8, 200.5, 381.4 and 509.2 kW, separately. For a full scale equivalent using the scale laws, these equate to fire sizes range from 16.2 to 123.7 MW. It should be noted that the combustion efficiency of fuel have not been considered here, which may cause the calculated HRR value larger than the real one, especially for the cases of multiple pans. However, the results could reflect the burning performance of different fuel areas to a certain extent.

The fuel pans were mounted on electronic balances with its four legs passing through the holes of fire-proof plate, as shown in Fig. 6, to protect the balances from high temperature. All pans were laid along the centerline in the middle of the tunnel with the longitudinal interval of 0.1 m (see Fig. 4). Fuel was poured into the pans through the ignition holes by a specially designed funnel