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Full-scale immersed tunnel fire experimental research on smoke flow patterns

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ABSTRACT

To research the smoke flow patterns and their effects on personnel evacuation during a tunnel fire, a full-scale model of an immersed 150 m tunnel was constructed, taking the Hong Kong–Zhuhai–Macao Bridge immersed tunnel in China as the prototype. A series of fire tests, including pool fires and vehicle fires, were developed to simulate a real fire scenario. The characteristic parameters describing the smoke flow were measured, including smoke layer height, smoke spread velocity, and CO concentration. Their development behaviors and main influence factors were explored, and finally smoke flow patterns were examined. The results showed that smoke stratification appeared, which was measured by smoke layer height. The smoke layer height distribution along the tunnel was found to obey a quartic polynomial trend (goodness of fit $> 95\%$). From this, the safety distances were predicted to be 20 m in windy conditions and 80–90 m in still (no wind) conditions. Thus, the longitudinal velocity plays a leading role. Around the fire source or in still conditions, the buoyancy of the smoke is the critical factor driving smoke flow; the influence of other factors is no more than ± 20%. However, other conditions depended on the ventilation state. CO concentration decreased sharply with increasing distance from the fire source. At a distance of 60 m, CO concentration decayed by 50%.

1. Introduction

The *Statistical bulletin of transportation industry development in 2016* (17 April 2017) stated that by the end of 2016 the number of national highway tunnels in China, including 815 extra-long tunnels ($L > 3000$ m, total length 3,622,700 m) and 3520 long tunnels ($1000\,\text{m} \le L < 3000$ m, total length 6,045,500 m), increased to 15,181 tunnels with a total length of 14,039,700 m. The number of tunnels increased by 1175 with an increased length of 1,355,800 m compared to the previous year. Tunnel fires are one of the common potential risks which restrain the development of tunnels on a longer and larger scale, when more tunnels bring convenience to transportation. Fires in the Mont Blanc tunnel, the Tauern tunnel, and the St. Gotthard tunnel were typical cases of serious fire disasters around the world (Vuilleumier et al., 2002). In recent years in China, fires in the New Qidaoliang tunnel in Gansu and the Yanhou tunnel in Shanxi both caused serious explosions and casualties (Yang, 2014). The accident investigation and analysis indicated that the main cause of casualties was toxic substances released by the incomplete combustion of fuels (Babrauskas et al., 1998, 1992). Thus, research on smoke flow patterns and thermophysical properties during the burning process in a tunnel is the basis and key point for solving tunnel safety problems (Yang et al., 2012; Hu et al., 2007; Lee and Ryou, 2006; Colella et al., 2009; Li et al., 2011). Previous studies focusing on the four main characteristic parameters of smoke flow have produced a great deal of information, including (1) the maximum temperature under the tunnel ceiling (Kurioka et al., 2003; Li et al., 2011; Liu et al., 2016; Tang et al., 2017); in particular the maximum smoke temperature model proposed by Kurioka et al. (2003); (2) longitudinal temperature decay (Kashef et al., 2013; Gong et al., 2016; Ji et al., 2016; Liu et al., 2017; Meng et al., 2017); in particular the effects of tunnel geometry and fire location on ceiling temperature decay studied by Kashef et al. (2013); (3) smoke back-layering length (Hu et al., 2008; Li et al., 2010; Gannouni and Maad, 2016; Fan and Yang, 2017); with a non-dimensional model to predict the back-layering flow length proposed by Li et al. (2010); (4) critical ventilation velocity (Tsai et al., 2010; Li et al., 2010; Tang et al., 2013; Chow et al., 2015); in which the critical velocity was measured in small-scale experiments and predicted by numerical simulations. In this paper, specific values (smoke spread velocity, smoke layer height, and CO concentration) were investigated in a realistic tunnel-fire scenario.

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It provided data which is the basis for further research on tunnel smoke flow behavior. Compared with small-scale models and numerical simulation models, a full-scale tunnel model is a more realistic reflection of an actual tunnel fire and the smoke flow state, because errors due to reduced scale and establishing numerical models vanish in full-scale experiments (Tian et al., 2017; Liu et al., 2016; Hu et al., 2013; Ji et al., 2012; Liu et al., 2017; Tang et al., 2017; Hu et al., 2013; Ji et al., 2015). In Europe, the United States, and other developed countries, a series of full-scale fire experiments have been carried out. The larger tests included the EUREKA 499 test programs (1990–1993) conducted in abandoned tunnels in Norway, Germany, and Finland, with an emphasis on smoke temperature, heat conduction, smoke flow rate, smoke concentration and rescue strategy. Tests on smoke control effects were conducted under different ventilation modes in the Memorial Tunnel in America (2001) (Buvik, 2006). The UPTUN project in Europe conducted in abandoned Runehamar tunnels in Norway emphasized the smoke spread behavior of burning container trucks, and the selection of fire-fighting devices (2003) (Ingason and Lonnermark, 2005; Lonnermark and Ingason, 2005; Ingason and Li, 2015; Ingason et al., 2012a, 2012b). The team at the University of Science and Technology of China conducted a series of tests in the Yangzong tunnel, Dafengyakou tunnel, and Yuanjiang No. 1 tunnel in Yunnan to investigate the temperature damping behavior of the smoke in the longitudinal direction. The prediction model regarding critical velocity and smoke back-layer length were discussed (2006) (Hu, 2006; Hu et al., 2005). Fire tests, fire source calibration, and alarm system tests were carried out in a tunnel in Shanghai, China, to obtain the key parameters, including smoke temperature, smoke concentration, general visibility and the visibility of exit signs, and accuracy of fire detection. The structure and fire-fighting devices were identical to those in existing maximum shield tunnels (2009).

The immersed-tube tunnel of the Hong Kong – Zhuhai – Macao Bridge is the longest immersed highway tunnel and the only deeply buried tunnel in the world, with a length of 5664 m. It is installed 40 m underwater, and is designed for a 120-year service life. Such an important and complex project, there is a big difference between existing full-scale tests and our study regarding the structural form and escape environment of the tunnel and how to ensure personnel safety in the event of a fire. The above questions were mainly solved, with the focus being on the criteria for personnel evacuation and provides reference material for the effective management of smoke and evacuation in the initial stage of a tunnel fire. To approach this, the scenario of a real tunnel fire was simulated by constructing a full-scale tunnel model in which both pool fires and burning vehicles were the fire sources. Based on this, the smoke spread process, the thermal parameters of the smoke, the behavior of the smoke flow, and its main factors were determined. A prediction of behavior of the thermal parameters for each working condition was proposed.

2. Experimental setup and conditions

2.1. Full-scale experimental tunnel

A full-scale experimental tunnel (150 m × 14.5 m × 7.1 m) comprising a tunnel structure and smoke extraction duct (Xu, 2014) was built to simulate the immersed tube tunnel of the Hong Kong – Zhuhai – Macao Bridge tunnel complex. Schematic diagrams are shown in Figs. 1 and 2. The model cross-section dimensions are shown in Table 1.

To determine smoke movement behavior most accurately in the test, adjustable resistance grilles were installed at both ends of the tunnel (Fig. 3) to compensate for the short experimental tunnel length by increasing local resistance to air flow in the model. The experimental results thus approximate the actual situation. The resistance grilles were composed of soft curtains 19 cm wide, based on equivalent friction theory, as follows:

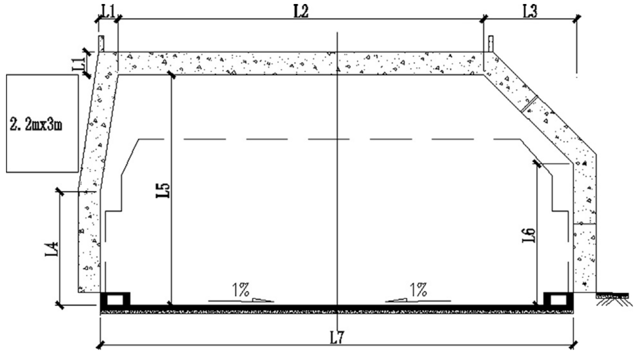

Fig. 1. Cross-section schematic of the experimental model of an immersed tube tunnel.

$$\xi_g = \frac{\lambda_m L_m}{d_m}, \tag{1}$$

where ξ_g is the loss coefficient of the resistance grilles; λ_m is the friction resistance coefficient; L_m is the length; and d_m is the equivalent diameter of the experimental tunnel. The design parameters of the resistance grilles are listed in Table 2.

2.2. Experimental apparatus and instrumentation

2.2.1. Smoke layer height measurement

The most intuitive and accurate way to obtain the smoke layer height, which is one of the most important parameters describing the behavior of the smoke flow, is a visual method. To approach this, the location system for observing smoke spread was coordinate lines painted on the side wall of the tunnel using a bright yellow fire-retardant coating. As shown in Fig. 4, vertical "1 m lines" 10 cm wide were drawn every 1 m, and "0.5 m lines" 5 cm wide were drawn midway between them.

To reduce visual errors, and to check the result, the smoke flow pattern was recorded at set time intervals by cameras installed in the side wall of the tunnel.

2.2.2. Smoke spread velocity measurement

A longitudinal airflow was generated by a jet fan located at the centerline of the tunnel. The specification of the jet fan was chosen to be Φ1000, 30 kW. A portable anemograph was used to measure the air speed generated by the jet fan and the speed at which the smoke spread. To ensure that combustion had reached the stable stage, measurements were conducted 3 min after the tests began. Fig. 5 shows the arrangement of monitoring points and fan position when the fire source was at different locations. The arrangement in the actual situation is shown in Fig. 6, where the monitoring points are denoted by solid dots and the hollow dots indicate the position of the jet fan.

2.2.3. Measurement of CO concentration in smoke

As shown in Fig. 7, smoke analyzers were installed in the experimental tunnel to detect CO movement in the personnel evacuation environment. To study the CO concentration longitudinally distributed at the inner and lower edges of the smoke layer, the smoke analyzers, in a arrangement consistent with the anemograph, were installed at different heights of the same cross-section, as well as at different longitudinal locations.

2.2.4. Fuel weighing system

The fire heat release rate was determined by the weight-loss method, whose accuracy depends on the accurate determination of the fuel quality. Two types of weighbridge were selected in accordance with the quality of the fuel, as shown in Table 3.

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