Tunnelling and Underground Space Technology 66 (2017) 134–146

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Full-scale experiments on fire characteristics of road tunnel at high altitude

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ARTICLE INFO

Keywords:
Tunnel fire
High altitude
Heat release rate
Temperature distribution
Smoke propagation

ABSTRACT

The high-altitude environment, with reduced atmospheric pressure, low air and oxygen density as well as low temperature, significantly affects the characteristics of the tunnel fire. In this paper, six full-scale fire tests were conducted in a road tunnel at high altitude of 4100 m. Three oil pools with areas of 0.8 m^2, 1.0 m^2 and 2.0 m^2 were employed as the fire sources. The Heat Release Rate (HRR), longitudinal and vertical temperature distributions, smoke propagation and back-layering were investigated in tests. The experimental results indicate that the Mass Loss Rate (MLR) at high altitude is lower than the theoretical one, and both the HRR growth rates and HRR growth rates per unit area increase with the pool size while the HRR per unit area seem to be independent of the pool size in this study. Additionally, the longitudinal dimensionless temperature with dimensionless distance were compared with the fire test conducted at normal altitude, arguing that the dimensionless temperature decays slowly at high altitude of 4100 m than at normal altitude of 773 m. The experimental results contribute to intensively understanding on fire characteristics of the tunnel at high altitude and to optimizing the fire detection and the emergency ventilation.

1. Introduction

The fire safety in the tunnel has attracted increasing attention due to several devastating fire accidents, which resulted in catastrophic consequences. For example, the Mont Blanc Tunnel fire on March 24, 1999, killed 39 people (Vuilleumier et al., 2002); and a highway tunnel fire in Shanxi Province, China, on March 1, 2014, caused 31 deaths (Yang, 2014). In recent years, an increasing number of super-long road tunnels at very high altitude have been constructed, which refer to the tunnel at an altitude ranging from 3500 m to 5500 m above the sea level (ISMM, 2005), such as the Balang Mountain Tunnel at altitude of 3800 m, the Queer Mountain Tunnel at altitude of 4300 m and the Changla Mountain Tunnel at altitude of 4500 m. The high-altitude environment is characterized by reduced atmospheric pressure, low air and oxygen density as well as low air temperature. The atmospheric pressure at altitude of 4100 m is 62.63 kPa and the air density is 0.8353 kg/m^3, far lower than the atmospheric pressure of 101.325 kPa and the air density of 1.29 kg/m^3 at normal altitude, respectively. The characteristics of tunnel fires at high altitude are significantly different from that at normal altitude. The low oxygen density is likely to induce incomplete combustion and has a significant impact on the Heat Release Rate (HRR), fire plume and the smoke temperature. The plume and smoke buoyancy force are related to the smoke temperature and the ambient air density influencing on the smoke movement, which may have an impact on the critical velocity and the back-layering. Furthermore, incomplete combustions of the fuel may contain massive CO and other toxic gases, accompanying with the low oxygen density, increasing the risk of the human health in a tunnel fire.

Some remarkable studies have been reported on the influence of altitude on the fire combustion. Wieser et al. (1997) conducted experiments in a mobile test room from the altitude of 400 m (97 kPa) to 3000 m (71 kPa) to investigate the influence of the high altitude on the Mass Loss Rate (MLR), arguing for a dependence of burning rate on pressure of p^{α} ($\alpha \approx 1.3$). A series of tests on the combustion characteristics of different scale fires have been conducted both at an altitude of 50 m (100 kPa) and at a high altitude of 3650 m (64 kPa) (Li et al., 2009; Fang et al., 2008, 2011; Tu et al., 2013; Niu et al., 2013; Hu et al., 2013a). These studies are mainly focused on the influence of the atmospheric pressure on the characteristics of the MLR, the HRR, the heat radiation, the flame height and the gas temperature. The results show that the MLR and HRR at high altitude are lower than that at normal altitude, leading to a long burning time at high altitude. The centerline plume temperature and the flame height at high altitude are higher than that at normal altitude while the radiation heat from the flame has a reverse trend. Zhang (2012) conducted full-scale fire tests in an inclined well and small-scale fire tests in the drain cavern of a super-long railway tunnel at high altitude of approximately 3300 m. The combustion characteristics, the smoke distribution, the vertical

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http://dx.doi.org/10.1016/j.tust.2017.04.007
Received 27 June 2016; Received in revised form 30 March 2017; Accepted 10 April 2017
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Table 1
A summary of full-scale and large-scale in-site tunnel fire tests.

Test tunnel, test date/Test series, test date	Tunnel altitude (m)	Length (m)	Height (m)	Cross section (m^2)	Fuel type	HRR (MW)	Ventilation (m/s)	Peak gas temperature (°C)	Measurements in the tests	Reference
Ofenegg Tunnel, 1965	Normal[a]	190	6.0	23.0	Petrol (6.6, 47.5, 95 m^2)	12–70	0–1.7	450–1325	T, u, CO, O_2, Smoke spread, m_f'	Haerter (1994), Ingason (2006)
Glasgow Tunnel, 1970	Normal	620	5.2	39.5	Kerosine (1.44, 2.88, 5.76 m^2)	–	–	–	T, Smoke spread	Heselden (1976)
Zwenberg tunnel, 1975	Normal	390	3.9	20.0	Petrol (3.4, 6.8, 13.6 m^2), Wood, rubber	7–21	–	300–1330	T, u, CO, CO_2, O_2, NO_x, THC, Visibility	Ingason (2006), Pucher (1994)
PWRI, 1980	Normal	700	6.8	57.3	Petrol (4, 6 m^2) Passenger car, bus	9.6–14.4	0.65–5.0	–	T, u, CO, OD, m_f', Radiation	Ingason (2006); PWRI (1993)
Kakeihigasi Tunnel, PWRI, 1980	Normal	3277	6.8	58.0	Petrol (4 m^2), bus	9.6	0–5.0	–	T, u, CO, OD, O_2, m_f', Radiation	Ingason (2006); PWRI (1993)
TUB-VTT, 1985	Normal	140	5.0	24–31	Wood cribs	8	0–0.4	400–680	T, u, CO, CO_2, O_2, m_f', Visibility, Smoke height	Keski et al. (1986)
EUREKA, 1990–1992	Normal	2300	4.8–5.5	25–35	Heptane, Wood cribs, cars, metro car, rail cars, HGV	6–128	0.3–0.7, 3.0–8.0	400–1300	HRR, T, u, CO, CO_2, O_2, SO_2, C_xH_y, NO, OD, m_f', Visibility, Soot, Smoke spread	Haack (1998)
Memorial Tunnel, 1993–1995	Normal	853	4.4, 7.9	36, 60	Fuel oil (4.5–45 m^2)	20–100	0–3.0	400–1360	T, u, CO, CO_2, CH_4, THC, m_f', Visibility, Stratification	Kelly and Giblin (1997)
Shimizu No. 3 Tunnel, 2001	Normal	1120	8.5	115	Petrol (1, 4, 9 m^2), car, bus	2.4–30	0–5.0	110–570	T, u, OD, Radiation	Shimoda (2002), Kunikane et al. (2002b)
2nd Benelux Tunnel, 2002	Normal	872	5.1	50	n-heptane + toluene (3.6, 7.2 m^2), car, van, wood, pallets	4.5–26	1.0–6.0	110–600	T, u, m_f', CO, OD, Radiation, Smoke front, Visibility, Fire detection	Kunikane et al. (2002a), Ingason (2006)
Runehamar Tunnel, 2003	Normal	1600	5–6	32–47	Cellulose, plastic, furniture	6, 66–202	2.0–3.0	267, 1250–1365	HRR, T, PT, u, CO, CO_2, O_2, HCN, H_2O, Isocyanates, OD, Radiation	Ingason et al. (2015b)
YuanJiang No. 1 Tunnel, etc., 2005–2007	770–2400	1032	7.1–8.9	68–108	Pool fire (1, 2 m^2), wood	0.18–4.2	0.5–3.0	39–130	HRR, T, CO, u, Smoke movement, Smoke height	Hu (2006), Hu et al. (2006, 2007a, 2007b, 2014b)
Singapore tests, 2012	Normal	600	7.3	39	Plastic + wood	27–150	2.8–3.0	–	HRR, T, u, CO, CO_2, O_2, Radiation	Cheong et al. (2013)
GuanJiao Railway Tunnel, 2012	3300	120	6.6	31	Pool fire (0.1, 0.27 m^2)	0.16–0.22	0.2–1.5	48–57	HRR, T, u, Smoke height, Smoke movement	Zhang (2012)
BaiMang Snow Mountain Tunnel, No. 1, 2013	4100	5180	6.85	58	Pool fire (0.8, 1, 2 m^2)	0.54–1.55	0–1.1	62–122	HRR, T, u, Smoke height, Smoke movement, Soot concentration	Present work

[a] 'Normal' means tunnel located at low altitude.

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