Tunnelling and Underground Space Technology 79 (2018) 274–285

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

An analysis of tunnel fire characteristics under the effects of vehicular blockage and tunnel inclination

Sina Shafee, Ahmet Yozgatligil*

Mechanical Engineering Department, Middle East Technical University, Universiteler Mahallesi, Dumlupinar Bulvari No:1, Ankara 06800, Turkey

ARTICLE INFO

Keywords:
Tunnel fire
Blockage
Inclination
Burning rate
Heat release rate

ABSTRACT

It is known that the blockage and inclination conditions of tunnels are among the important factors affecting fire safety considerations, as these factors could change the characteristics of possible fire incidents as well as smoke movement in tunnels. In the present work, we analyze the variations of the tunnel fire burning rate, heat release rate and smoke backlayering as being functions of these two factors. Ethanol pools were used as fire sources in a reduced scale tunnel model with longitudinal ventilation ranging between 0 and 1.5 m/s. The blockage ratio of the tunnel, which was defined as the ratio of the cross-sectional area of the blockage to that of the tunnel, was tested under three cases: 0% (i.e., no blockage), 14% and 56% blockage. The latter two blockage ratios respectively correspond to that of a typical small vehicle and a railroad carrier. The tunnel inclination grade was varied between −6% and +3% to represent uphill and downhill slopes. Numerical simulations were also performed using Fire Dynamics Simulator (FDS) to rationalize some of the experimental results. Measurements and predictions indicated that the blockage affects the burning rate of tunnel a fire due to changes in the air entrainment at wake flow, local ventilation over the fire and flame dragging. Increasing the fire-blockage separation distance had an adverse effect on the burning rates. The temperature results emphasized the effect of blockages on tunnel ceiling temperatures, which increased as high as 300% compared to that of the no blockage case. The results indicated the major effects of the tunnel sloping grade on the fire heat load as well as the tunnel ceiling temperature. The critical ventilation velocity was achieved in the range of 0.75–1.25 m/s for the limiting cases of −6% and +3% tunnel inclination, for which a fit was proposed as a function of inclination grade. Finally, a statistical model based on an analysis of variance approach was applied on the obtained results, which demonstrated that among the factors contributing to the fire heat release rate variations in this study, the ventilation velocity accounted for 45% of the variation, followed by tunnel blockage at 25%, and inclination at 19%.

1. Introduction

Due to the confined nature of tunnels, the temperatures become extremely high in a short period of time when there is a fire incident. This is mainly due to the re-radiation of heat from the walls and the smoke layer. Heavy traffic and/or accidents, which can lead to the obstruction of tunnels, make it even more difficult to counter possible tunnel fire hazards. This is because a blockage in the upstream of a tunnel fire can alter the smoke movement and consequently, the ventilation requirements of the tunnel. A related concern is the effect of downhill (positive) and uphill (negative) tunnel slopes due to the effect of fire-induced buoyancy. These factors need to be considered in the design of fire protection equipment. Owing to the rise in serious fire accidents, over the past few decades, there have been numerous studies that investigate tunnel fire characteristics by means of large or reduced scale experiments, as well as numerical simulations. These studies have contributed to the now rich literature on tunnel fire dynamics, related safety measures and the development of key safety standards (AIPCR, 1999; Babrauskas and Peacock, 1992; Beard and Carvel, 2005; Bechtel, 1995; Carvel et al., 2001a,b; Chen et al., 2011a; Danziger and Kennedy, 1982; Vuilleumier and Crausaz, 2002; Hu et al., 2006; Ingason and Lönnermark, 2005; Kurioka et al., 2003; Lee and Ryou, 2006; Leitner, 2001; National Fire Protection Associationre, 2011; Roh et al., 2008, 2007; Stahlanwendung, 1995; Wu and Bakar, 2000; Yuan and You, 2007).

The critical velocity is defined as the minimum ventilation velocity required for the prevention of smoke movement in the upstream direction. In a study into the effect of a downhill inclination on the critical ventilation velocity in tunnel fires, the critical velocity was shown to be larger in cases of downhill-inclined tunnel fires compared to a

* Corresponding author.
E-mail addresses: sina@metu.edu.tr (S. Shafee), ahmety@metu.edu.tr (A. Yozgatligil).

https://doi.org/10.1016/j.tust.2018.05.019
Received 18 August 2017; Received in revised form 20 April 2018; Accepted 16 May 2018

Nomenclature

A	fire surface area, m^2
c_p	specific heat, J/mol K
D^*	characteristic fire length, m
E	energy release, J
Fr	Froude number
g	gravitational acceleration, m/s^2
H	tunnel height, m
i	data scan number
L	characteristic length, pool size, m
m	fuel mass, kg
m'''	burning rate, kg/m^2
$\dot{Q}$	heat release rate, W
$\dot{Q}*$	non-dimensional heat release rate
r	pool radius, m
S	separation distance, cm
t	time, s
T	temperature, K, °C
TC	thermocouple in combustion section
TD	thermocouple in downstream section
TU	thermocouple in upstream section
u_i	relative uncertainty
U	ventilation velocity, m/s
V'	volumetric flow rate, m^3/s
x_i	independent variable
X	species mole fraction
A	measured values from gas analyzer
°	standard conditions
a	airflow
Cr	critical
F	full scale (real scale)
fu	fuel
M	model
ρ	density, kg/m^3
ε	Kurioka et al. model coefficient
γ	Kurioka et al. model coefficient
ϕ	oxygen depletion factor
θ	tunnel inclination angle

horizontal tunnel (Atkinson and Wu, 1996). In more recent works, Oka and Imazeki performed a series of systematic experiments to measure the tunnel ceiling jet temperature and proposed a correlation for predicting the ceiling temperature distribution in uphill-inclined tunnels (Oka and Imazeki, 2015). They used a tunnel model that was 10 m in length, 0.75 m in width and 0.45 m in height with inclination grades up to 10° and used methanol/LPG fuel as fire sources. They also compared the results obtained for the tunnel ceiling temperature distribution with those of an unconfined ceiling jet. The same authors had previously investigated the characteristics of the ceiling jet under tilting and unconfined conditions using pool fires as the fire source (Oka and Imazeki, 2014a,b) and elsewhere in (Oka et al., 2010). They proposed empirical formulations for the temperature and velocity distribution of the ceiling jet profile that are functions of the inclination angle and the distance from the ceiling. Oka et al. used a 1:23.3 reduced scale tunnel model to investigate the ceiling jet flow and its temperature distribution in inclined tunnels and showed that the confinement conditions of a tunnel also results in a thicker ceiling jet layer under horizontal and inclined tunnel conditions (Oka et al., 2013).

The effect of tunnel blockage and fire-blockage distance on tunnel fire characteristics has been investigated by a number of researchers (Lee and Tsai, 2012; Tang et al., 2017a,b; Tang et al., 2013). Tang et al. used a 1/5 scale model tunnel to show that increasing the blockage-fire distance decreases the backlayering length and critical velocity to an asymptotic value (Tang et al., 2013). FDS is among the most common models available for fire simulation within the fire research community (Hu et al., 2008; McGrattan et al., 2008; McGrattan et al., 2000). This model was used to study the effect of a tunnel blockage that occupied 31% of a tunnel's cross-section (Gannouni and Maad, 2015). The location of blockage relative to the tunnel floor was varied but the fire-blockage distance was kept constant in their study. Measurements from an earlier reduced scale study (Li et al., 2010) were used to validate the FDS simulations. They showed that the blockage decreased the critical velocity compared to that of a free fire. A train mock-up model inside a reduced scale subway tunnel along with FDS simulations was used (Zhu et al., 2017) to investigate the effect of a downhill tunnel slope on the critical ventilation velocity under blockage conditions. A propane burner was used to generate fires with heat loads up to 33.52 kW downstream of train blockage. They concluded that such a blockage considerably affects the smoke backlayering length and that the critical ventilation velocity increases as the downhill tunnel inclination grade increases.

In our previous works, we studied adjacent fire interactions in tunnels and the effect of the longitudinal ventilation velocity, among other factors, on the variation of fire burning rate phasing, smoke backlayering and temperature distribution in tunnel fires with no blockage and at horizontal conditions (Shafee et al., 2017; Shafee and Yozgatligil, 2018). The results showed that the burning rate of standalone tunnel fire can increase by up to 130%, mainly due to interactions from the secondary fire source and fire merging. In our current work, we further investigated tunnel fire characteristics under the effects of blockage and inclination. Numerical simulations by FDS were also used to accompany the experimental results. A statistical approach was incorporated to estimate the key factors affecting the tunnel fire heat release rate. This topic is of special importance in tunnel fire research because there is an increased risk of trapped vehicles upstream of a tunnel fire scenario, which affects the local flow conditions as well as fire characteristics. Most tunnel fire studies do not take into account the effect that tunnel blockage and inclination may have, which are conditions that a great number of underground and road/railroad tunnels could present.

2. Experimental setup and methods

The experiments were conducted in a 1/13 scale model tunnel, which represented an arched underground metro tunnel in Istanbul, Turkey. The model was constructed based on Froude modelling (Quintiere, 2006, 1989). Due to the complex nature of a confined fire, it is not possible to achieve complete similarity between the scale model and the actual object. Therefore, Froude modelling is applied in most of the reduced scale experimental work related to tunnel fires in which partial scaling is maintained between the model and the real tunnel (Ingason and Li, 2010; Quintiere, 2006). The applicability of Froude modelling for turbulent, buoyancy-driven flows is discussed elsewhere (Kang, 2010; Quintiere, 1989; Roh et al., 2008, 2007; Tang et al., 2013). Correlations for the heat release rate, characteristic velocity and temperature were established between the model and the real scale tunnel based on Froude modelling, given in Eq. (1).

$$\frac{\dot{Q}_M}{\dot{Q}_F} = \left(\frac{L_M}{L_F}\right)^{5/2}, \frac{U_M}{U_F} = \left(\frac{L_M}{L_F}\right)^{1/2}, T_M = T_F \tag{1}$$

A full description of the experimental setup and test procedure can be found in the authors' previous works (Shafee et al., 2017; Shafee and Yozgatligil, 2018). In brief, the arched insulated tunnel was 40 cm in width, 36.4 cm in height and approximately 10 m long. The schematics of the tunnel model, the measurement layout and the locations can be