Fire Safety Journal 96 (2018) 115–123

Contents lists available at ScienceDirect

Fire Safety Journal

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

An experimental study on the burning rates of interacting fires in tunnels

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ARTICLE INFO

Keywords:
Burning rate
Heat release rate
Interacting fires
Pool fires
Reduced scale tunnel

ABSTRACT

Multiple fires may occur in close proximity in process industries, power generation and fuel storage facilities and confinement conditions such as tunnels, which can lead to a considerable alteration in fire characteristics and safety design. The topic is of significant importance to the fire safety research because there is little work in the literature that investigates the case of interacting fires, which have a destructive potential. In this work, we study the effects of an adjacent fire source on the burning rate and heat release rate characteristics of tunnel fires. Square ethanol pools of 10 and 15 cm in size and 0.22–1 cm in depth were used as fire sources in a reduced scale tunnel model. Ventilation to the tunnel was varied between 0 and 1.5 m/s. Pool fires were configured in single and dual pool orientations. Variations in the pool fire burning rates were discussed as being functions of pool size and depth, and a result of the interaction with the secondary fire. The maximum burning rate enhancement factor, defined as the ratio of the parameter for interacting fires to non-interacting ones, was shown to be 2.3. This was due to the enhancing effect of the secondary fire on the heat feedback to the fuel, and the increased combustion mass transfer. Tests with relatively larger pool sizes burned faster, with an advanced onset of the transition to a bulk boiling phase, which was attributed to the controlling heat feedback mechanism associated with the pool size.

1. Introduction

Research on tunnel fire safety has gained more importance owing to the rise in serious fire accidents, possibly resulting from the increased construction and utilization of road and railroad tunnels, which can now be many kilometers in length. The literature indicates that the source of tunnel fires is generally burning carriers, heavy good vehicles (HGVs) and pool/spill fires following the leakage of combustible materials from tankers [1–3]. Consequently, pool fires are of special interest to the fire research community in general and tunnel fire safety in particular. Pool fires are also recognized as a source of industrial fires [4,5]. There is an abundance of experimental and numerical research literature on pool and tunnel fires. The critical ventilation velocity (defined as the minimum ventilation velocity required for the prevention of smoke movement in an upstream direction), smoke flow backlayering, tunnel temperature distribution, fire Heat Release Rate (HRR) and burning rate have been studied using real scale or reduced scale tunnel models. These works have contributed to the current knowledge on tunnel fire dynamics and the development of fire safety standards [6–20]. Among the above factors, the burning rate and HRR of a fire are considered to be the most prominent factors in considering pertinent fire hazards [21,22].

Research on pool fires was pioneered by Blinov and Khudiakov [23] and elsewhere by Rasbash [24]. In more recent works, pool fire combustion has been characterized according to fuel type, pool size, the dominant heat transfer regime and flame attributes [25–28]. An informative summary of relevant studies on the matter was given by Ditch [29] and elsewhere by Hu [30]. Chen et al. investigated the burning rates and temperature variations of 0.2 m circular n-heptane pool fires under quiescent conditions [31]. The results indicated that there are two-stages in the increase of the burning rates of a fire, in which the second peak corresponds to fuel bulk boiling. The effect of vessel materials and freeboard heights on the burning rates of small ethanol pool fires was investigated by Dlugogorcki and Wilson [32]. Glass, copper, and steel were used as vessel materials. They concluded that the effect of the lip height could be a controversial aspect of the study of pool fires.

Shafee et al. investigated variations in the Mass Loss Rate (MLR) of n-heptane pool fires in a 1/13 scale model of an underground tunnel [33]. Square and rectangular pans were used for the pool fire. The critical ventilation velocity was shown to be achieved at around 1 m/s in the model, which corresponded to 3.6 m/s in the real scale tunnel. H.Y. Wang simulated octane pool fires in a ventilated real scale tunnel using Fire Dynamics Simulator (FDS) numerical code [34]. Large Eddy Simulation (LES) was used to model turbulence in this work. FDS incorporates a finite difference solver, which is commonly used in fire simulations by

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https://doi.org/10.1016/j.firesaf.2018.01.004
Received 30 July 2017; Received in revised form 21 December 2017; Accepted 9 January 2018

Nomenclature

A	Pool surface area, m^2
B	Spalding mass transfer number (thermodynamic parameter measuring the ratio of fuel's tendency to vaporize due to the heat of combustion to the resistance against it), non-dimensional
H	Heat of combustion/vaporization, J
L	Characteristic length, m
m	Fuel mass, kg
$m^{'''}$	Burning rate, kg/m^{2}s
$\dot{Q}$	Heat release rate, J/s
T	Temperature, K, °C
u	Relative uncertainty
t	Time, s
U	Velocity
Subscripts	
c	Combustion
F	Full scale
fu	Fuel
v	Vaporization heat
s	Surface
M	Model

the fire research community, and was developed by the National Institute of Standards and Technology (NIST) [35]. In the simulation, the HRR was varied between 2 and 50 MW with increasing pool diameter. The results showed a good agreement between the model and real scale measurements in terms of the temperature distribution at different heights above the pool fire along the tunnel axis. The model's predictions were also compared with empirical correlations for smoke backlayering length and flame length. In another work, the liquid fuel evaporation model and thermal boundary conditions in FDS were modified to improve the steady-state burning rate predictions to beyond those obtained by the default model in FDS [36]. The modified model was used in the simulation of 0.4 m^2 hydrogenated tetra-propylene pool fires in open space and ventilated compartments. The burning rate results indicated that there is a very good agreement between measurements and the modified model's predictions.

Another important aspect of fire investigation is the study of interactions between fire sources, which may result in flame merging, the spread of fire and significant changes in the burning rate and heat feedback to the fuel surface. Wang et al. examined the merging behavior of open pool fires under crosswind effect [37]. They used a wind tunnel setup to create the crosswind. The results showed that merging increases the pool fire burning rate and flame height by up to 100% for a constant fuel surface area. In other works, the critical conditions for flame merging in an open space were also investigated, for which correlations were expressed as a function of the number of pools and the pool diameter [38,39]. There are also several studies which propose empirical models for estimating the burning rates and HRR of multiple pool fires at varying separation distances in an open space [40–42]. There is little work in the literature that investigates the case of two (or more) fire sources in the open air and even less work that is done under confinement conditions. In this sense, this work is an attempt to provide some new information on the physics of interacting tunnel fires and to present a wide set of data to be used as a validation case for CFD modeling purposes.

2. Experimental setup and methods

Tests were conducted in a 1/13 scale tunnel model of an arched underground tunnel in Istanbul, Turkey. The model tunnel was constructed based on Froude modeling [43,44]. Due to the nature of complex fire dynamics, especially in the case of confined fires, it is impossible to achieve complete similarity between the scale model and the real object. Therefore, Froude modeling is commonly used in experimental fire research in which partial scaling is maintained between the model and the real scale [44,45]. The suitability of Froude modeling for turbulent buoyancy-driven flows is discussed elsewhere as it is considered one of the most useful applications of scale modeling [7,43,46–48]. According to Froude modeling, the relationships for the HRR, characteristic velocity and temperature can be established between model and the real scale tunnel as given in equation (1),

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

where $\dot{Q}$ is the HRR of the fire, T is the gas temperature in Kelvin, and U is the characteristic flow velocity (i.e. ventilation velocity). The same experimental setup was used in the authors' previous study on pool fires, and a full description of the specification of the model tunnel and the experimental procedure can be found there [33]; in brief, the tunnel model was 40 cm in width, 36.4 cm in height, and 9 m in length. The tunnel was insulated to minimize heat loss, and it consisted of five 1.5 m long compartment modules, an entrance, and a chimney section. A flow straightener was mounted in the upstream section of the tunnel to rectify the ventilation airflow. Pool fire tests were conducted in the combustion section of the tunnel. The schematics of the real scale tunnel, as well as the reduced scale model and the measurement layout, are given in Fig. 1. Due to width limitations, only 10 and 15 cm square pools were used. Nevertheless, the generated fire loads corresponded to 2–20 MW in the real scale tunnel, the equivalent of a fire scenario consisting of small-to-large road/railroad transportation vehicles. Pools were configured in Single Pool (SP) or Dual Pool (DP) orientations depending on the scenario and placed in the center of the combustion section. The tray rim edges were flush, and heat loss through the bottom side of the fuel trays was minimized using insulation boards.

Mass loss histories of the fuel were measured using two precision, internally-stabilized load cells with a sampling frequency of 5 Hz and a readability of 0.1 g. The derivative of the mass loss history was used to obtain the MLR. The burning rate of the fuel was calculated as the MLR per unit area of the pool (0.01 m^2 and 0.0225 m^2) as given in equations (2) and (3).

$$m^{'''}=\frac{dm_{fu}/dt}{A_{Burned}} \tag{2}$$

$$-\left(\frac{dm_{fu}}{dt}\right)_i=\frac{-m_{i-2}+8m_{i-1}-8m_{i+1}+m_{i+2}}{12\Delta t}\quad \text{where } i \text{ is data scan number} \tag{3}$$

Similar to the method commonly used in investigating batch pool fires elsewhere [7,21,31,49], we also report the burning rate values based on a time-averaged maximum value. This peak is obtained in the "quasi-steady-state" combustion period, in which the burning rate is constant for a duration of time, as illustrated in Fig. 2. The combined relative uncertainty of the burning rate was calculated according to the principle of propagation of uncertainty [50]. The burning rate is a function change of fuel mass, the time interval and the fuel surface area in equation (2). The combined relative uncertainty of the burning rate measurements was then obtained according to equation (4).

$$\begin{aligned} u_{m^{'''}} &= \pm\left(\sum\nolimits_{i=1}^{n}\left[\frac{x_i}{m^{'''}}\frac{\partial m^{'''}}{\partial x_i}u_i\right]^2\right)^{1/2} \\ &= \pm\left(\left[\frac{\Delta m}{m^{'''}}\frac{\partial m^{'''}}{\partial \Delta m}u_{\Delta m}\right]^2+\left[\frac{\Delta t}{m^{'''}}\frac{\partial m^{'''}}{\partial \Delta t}u_{\Delta t}\right]^2+\left[\frac{A}{m^{'''}}\frac{\partial m^{'''}}{\partial A}u_{A}\right]^2\right)^{1/2} \end{aligned} \tag{4}$$