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Experimental study on flame merging behaviors from two pool fires along the longitudinal centerline of model tunnel with natural ventilation

Jie Ji[a,b,*], Huaxian Wan[a], Zihe Gao[a,**], Yanyun Fu[a], Jinhua Sun[a], Yongming Zhang[a], Kaiyuan Li[c], Simo Hostikka[c]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, JinZhai Road 96, Hefei, Anhui 230026, China
[b] Institute of Advanced Technology, University of Science and Technology of China, Hefei, Anhui 230088, China
[c] Department of Civil Engineering, School of Engineering, Aalto University, 02150 Espoo, Finland

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ABSTRACT

A set of experiments was conducted in a model tunnel to study the interaction behaviors of two pool fires. Square heptane pool fires with side lengths of 10 cm, 13 cm and 16 cm were used as the fire sources. In the experiments, two identical fires were located at the longitudinal centerline of tunnel. The fire spacing was set as an integral multiple of the half pool length. The mass loss rates of two fires in tunnel were compared with fires in the open space and it was explained from the viewpoints of the interactive burnings and the heat feedback mechanism. Results showed that as the spacing decreases, the mass loss rate increases first and then decreases. Similar trends can be found in heat fluxes received by objects at the pool surface level. With decreasing the spacing, the longitudinal ceiling flame shapes are divided into four categories, i.e., non-interaction flames, tilted flames without merging, merging ceiling flames and merging vertical flames. The image processing method is used to judge the flame merging and to obtain the position of merging point and the flame length. An expression correlating the distance from the merging point to the ceiling and the normalized spacing is established. By using dimensional analysis and introducing a correlation factor, a correlation for predicting the effective ceiling flame length is developed, involving the heat release rate, pool size, spacing and effective tunnel height. Moreover, a method to estimate the flame radiant fluxes received by the objects located in the lower layer of tunnel with vertical and horizontal orientations is proposed to further reveal the mechanism of heat radiation from two interacting fires in tunnel.

1. Introduction

Two or more fires burning simultaneously is termed as multiple fires. When multiple fires are located sufficiently close, they will influence each other and lead to more severe outcomes. Since the 1950s, a large amount of accidents involving multiple fires have been reported. The most notable one is the earthquake fire that took place in Japan on March 11, 2011 [1]. A tsunami induced by the massive earthquake damaged and ignited a 980 kL gasoline tank, the resultant fire spread to the tanks nearby and caused a significant multi-fire accident [1]. More examples can be found in Ref. [1]. The burning behaviors of multiple fires can be very different from a single fire due to the interaction of adjacent fires. Once the fires are located sufficiently close to each other, the air entrainment around the flames could be restricted and the resulting pressure drop between fires might lead to flame merging which will cause the increase of flame height compared to a single fire [2,3]. The flame merging will make the fire more destructive, leading to difficulties in firefighting and may even lead to fire whirls [2–5]. Therefore, it is worthwhile to study the interacting fires.

In the past decades, numerous studies have been carried out on multiple fires. However, most of them [2–17] were conducted in open space to investigate the effects of fuel type, fire shape, size, number, spacing and array pattern on the mass loss rate (MLR), flame height, flame merging, heat feedback, fire whirl, etc.. For example, Weng et al. [2], Kamikawa et al. [3] and Fukuda et al. [4] studied the effects of fire spacing and heat release rate (HRR)

* Corresponding author at: State Key Laboratory of Fire Science, University of Science and Technology of China, JinZhai Road 96, Hefei, Anhui 230026, China.
** Corresponding author.
E-mail addresses: jijie232@ustc.edu.cn (J. Ji), gaozihe@ustc.edu.cn (Z. Gao).

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Nomenclature

a	coefficient in Eq. (8)
b	coefficient in Eq. (8)
c	correction factor in Eq. (11)
c_f	modified correction factor in Eq. (12)
c_p	specific heat of air (kJ/(kgK))
D	pool length (m)
D_0	equivalent pool length without spacing (m)
D_{eq}	equivalent pool diameter (m)
F	geometrical view factor
g	gravitational acceleration (m/s^2)
H	tunnel height (m)
h_c	convective heat transfer coefficient (kW/m^{2}K)
H_{ef}	effective tunnel height (m)
H_{sur}	distance from the fuel surface to the ceiling (m)
k	extinction coefficient (m^{-1})
L_{ef}	effective flame length (m)
L_f	flame length (m)
L_{height}	vertical flame height (m)
L_{length}	total longitudinal flame length of each fire (m)
L_{total}	total longitudinal flame length of merging flames (m)
$\dot{m}$	mass loss rate (g/s)
$\dot{m}''_\infty$	infinite-diameter pool mass loss rate (kg/(m^{2}s))
n	fire number
N	fire number of $N \times N$ fire array
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_0^*$	normalized heat release rate without spacing
$\dot{q}''_{conv,\ wall}$	convective heat flux at wall (kW/m^2)
$\dot{Q}^*_{DH_{ef}}$	normalized heat release rate in Eq. (7)
$\dot{q}''_{exter,rad}$	external radiant flux (kW/m^2)
$\dot{q}''_{flame,rad}$	flame radiant flux (kW/m^2)
$\dot{q}''_{sur}$	surface heat flux (kW/m^2)
r_f	radial flame length (m)
S	fire spacing (m)
T_0	ambient temperature (K)
T_{gas}	gas temperature (K)
ΔH_c	heat of combustion per unit fuel mass (MJ/kg)

Greek symbols

α	coefficient in Eq. (13)
β	coefficient in Eq. (13) and mean beam length corrector
ε	emissivity
θ_m	distance from the merging point to the ceiling (m)
ρ_0	ambient density (kg/m^3)
σ	Stephan–Boltzmann constant (W/(m^{2}K^4))
τ	transmissivity
χ	combustion efficiency
$\chi_{conv,wall}$	ratio of convective heat flux at wall to the total measured wall heat flux
$\chi_{flame,\ rad}$	fraction of the flame radiant flux received by object
$\chi_{exter,\ rad}$	fraction of the external radiant flux received by object
χ_m	combustion efficiency of merging flames

Subscript

c	cylinder
d	disk
f	flame
H	horizontal direction
rad	radiation
V	vertical direction

on the merging flame height of multiple fires in $N \times N$ square arrays (N varied from 2 to 4). They concluded that the spacing has a weaker impact on the flame merging compared to the fire number and HRR. Weng et al. [5] studied multiple wood crib fires and found that increasing the spacing and the burner number enhanced the combustion efficiency. Huffman et al. [6] found that the MLR of multiple pool fires with luminous flames increases and then decreases with decreasing the spacing. These results were also identified by Grumer and Strasser [7] using solid fuel beds and Liu et al. [8] using heptane pool fires. Huffman et al. [6] explained the non-monotonous trend as a result of the heat feedback to fuel surface. Liu et al. [8] further indicated that it is caused by the competition between the heat feedback enhancement and the air entrainment restriction. Considering that the fire number is still limited in the former studies, Liu et al. [8–10] experimentally studied the burning rate of multiple pool fires with the square fire array number up to 15×15 and concluded that the fluctuation mode of burning rate varies with the fire number. Refs. [11–15] studied the critical conditions under which the flame merging takes place and reported various criteria of flame merging. By introducing a correction factor, Sugawa and Takahashi [14] proposed a set of empirical correlations for flame heights from 2 to 4 interacting flames with symmetrical configurations in open space. Delichatsios [15] theoretically deduced the merging flame height for multiple fires in open space by taking into account the air entrainment. Lu et al. [16] studied the merging behaviors of flames ejected from two parallel windows and concluded that the flame height is affected by the height of merging point. Vasanth et al. [17] conducted numerical simulation on multiple fires in open space.

In confined spaces such as in tunnels, multiple vehicle fires might take place during accidents [18]. Lönnermark and Ingason [19] found that in major tunnel fires, at least 10 heavy goods vehicles were involved together with other vehicles. Unfortunately, little effort has been put with respect to multiple fires in tunnels. Tsai et al. [20] conducted experiments and simulations to study the effects of fire size and spacing on critical ventilation velocity for two fires in tunnels. Ingason and Li [21] studied the impact of ventilation on maximum temperature beneath the ceiling using 1–3 wood crib fires in a model tunnel. Hansen and Ingason [22] found that the ignition time of adjacent wooden pallet decreased with increasing the longitudinal ventilation in a model tunnel. Chen et al. [23] found that the two methanol fires would shift to the entrance of tunnel with lower sealing ratio when the two ends of tunnel are sealed with different ratios. However, detailed investigations on the critical condition of flame merging, the MLR, the flame height and the heat flux in tunnels were not conducted in literatures. The present paper attempts to bridge this knowledge gap. The mechanisms of heat feedback and air entrainment induced by multiple fires in tunnel are different from those in open space. When two fires are close, the heat feedback received by the fuel surface comes from its own flame and the adjacent flame, the smoke and the tunnel boundaries, resulting in the increasing of burning rate. Under high HRRs, the flames can impinge on the ceiling and lead to the ceiling flame merge. As a result, the ceiling heat flux will increase dramatically in the flame region [24–27], which is a more dangerous condition. The effect of heat feedback on combustion has been studied extensively in open space while only few works conducted in confined spaces. Nasr et al. [28] found that the thermal radiation received by the fuel can be subdivided into the flame radiation and the external radiation in an enclosure and they developed an original method to calculate the two compo-