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Full Length Article

Flame base drag of pool fires with different side wall height in cross flows: A laboratory-scale experimental study and a new correlation

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HIGHLIGHTS

- Effect of pool side wall height on flame base drag length quantified.
- A non-dimensional approach proposed for flame base drag length evolution.
- A new general correlation proposed well collapsing the data.

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ABSTRACT

This paper investigates the effect of pool side wall height on flame base drag behavior of pool fires in cross flow of air, which has not been quantified in the literatures. Laboratory-scale experiments are carried out to measure the flame base drag lengths of pool fires using gaseous square quartz sand box as burner of different sizes (10 cm, 15 cm and 20 cm), employing propane as fuel with pool side wall heights of 2 cm, 3 cm, 4 cm and 5 cm above the ground. It is found that flame base drag length is smaller when the pool side wall is higher and increases with increase in fuel supply rate or cross flow air speed, meanwhile decreases with increase in pool size. A new formula is proposed to interpret the evolution behavior that the flame base drag length in relation to these quantities, based on the interaction of cross flow to the buoyancy of the fire. The proposed formula is shown to well correlate the data of different pool sizes and side wall heights non-dimensionally by Froude number, dimensionless heat release rate and the density ratio between the fuel and air.

1. Introduction

Storage tank (pool) fire will result in serious hazards that its burning behaviors have been studied for decades. There are already extensive works reported in the literatures addressing its combustion behaviors and flame characteristics in quiescent air [1–4]. However, the studies on its behaviors in cross flows of air are still limited, for which previous findings can be found are for the burning rate [5–7] and more recently about the change of heat feedback evolution [8,9], flame tilt [10,11] and flame length [10,12,13] with cross flow air speed.

Flame base drag is a special phenomenon of pool fire behavior in cross flow of air [14–20], which is observed as an extension of flame base outside the pool along the downstream ground. Its mechanism is explained [14] as when a pool fire subject to a cross flow of air and if the density of the fuel vapor is higher than that of the surrounding air, the heavier vapors close to the liquid surface are dragged in the downwind direction. It is remained in the ground level and burns, with its density finally being heated up to be less than that of the ambient air after traveling a certain distance and then rising up again, thus forming an extension of flame base with a certain length (distance) downstream of the pool. The flame base drag behavior will pose serious adverse impact by directly igniting the combustible downstream nearby, that the evolution of its length with cross flow air speed is an important behavior to be quantified and modeled. Meanwhile, the heat transfer to the ground can be significantly changed with or without flame drag.

However, the measured data as well as studies on flame base drag are still very limited for which the only literatures can be found are [14–20], which are mainly concerning the flame base drag length evolution with cross flow air speed. The data achieved [18,20] for the total flame base length ($D + L_{drag}$) of different pool sizes and cross flow air speed ranges are correlated non-dimensionally by Welker and Sliepcevich [14], Moorhouse [16],

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Nomenclature

c_p	specific heat
D	length of square pool (m)
Fr_w	cross flow of air Froude number
$Fr_{w,10m}$	Froude number based on wind speed measured 10 m above ground
g	gravitational acceleration (9.8 m/s^2)
H	side wall height of pool (m)
L_{drag}	flame base drag length (m)
$\dot{Q}^*$	non-dimensional heat release rate $\left(\dot{Q}^* = \frac{\dot{Q}}{\rho_a c_p T_a \sqrt{gD}D^2}\right)$
$\dot{Q}$	heat release rate (kW)
T_a	ambient air temperature
$\dot{V}_f$	fuel supply rate (m^3/h)
w	inverse volumetric expansion ratio of gases due to combustion

Greek symbols

Γ	coefficient defined by Eq. (2)
ρ_a	density of ambient air (kg/m^3)
ρ_f	density of flame (kg/m^3)
ρ_v	density of fuel vapor at boiling point (kg/m^3)
v_a	kinematic viscosity of air (m^2/s)

Subscript

a	property of ambient air
$drag$	property of flame drag
f	property of fuel
v	property of fuel vapor
w	property of cross flow of air

Nedelka et al. [17], Johnson [18], Mudan [19] and Lautkaski [20] to develop semi-empirical formulas, based on the Froude number

$$Fr_w = \frac{U_w^2}{gD} \tag{1}$$

and vapor–air density ratio (ρ_v/ρ_a) by power law functions, where ρ_v and ρ_a are the densities of fuel vapor at the boiling point and ambient air respectively, D is the pool size (diameter or square length), L_{drag} is the flame base drag length beyond the pool base. They suggested different correlation constants (1–3.57) and power law indexes (0.122–1) for Froude number with a same power law index (0.48) for the density ratio, as summarized in Table 1. It can be seen from these formulas that, when the cross flow air speed is zero (the RHS of these correlations is zero), the flame base drag length (L_{drag}) should also be zero; however, the LHS is one in these correlations. Recently, Raj [15] proposed another new formula by introducing the volumetric expansion ratio, correlating non-dimensionally the net flame base drag length (L_{drag}) against Γ, Re number $\left(\frac{U_w D}{v_a}\right)$ and Froude number, where Γ is defined as:

$$\Gamma = 25\left[\frac{\omega}{(1-\omega\rho_a/\rho_v)(\rho_a/\rho_v)^{1/2}}\right]^{1/2} \tag{2}$$

whose value is suggested [14] to be constant (ranged in 27.93–29.10 for different fuels) independent of pool size and cross flow air speed, where ω is the inverse volumetric expansion ratio of gases due to combustion [14] and the constant 25 in Eq. (2) is obtained by correlating the experimental data in [12,15,21]. However, there is still quite considerable scattering in the proposed correlation (Fig. 5 in [15]). A summary of these correlations along with their experimental conditions (pool sizes; cross flow air speed ranges, fuels) are shown in Table 1.

However, for all these previous data obtained and correlations developed, the effect of pool side wall height is not considered. That is, for the previous experiments, the pool height is all nearly zero (for laboratory experiments, the pool rim is almost flush with the ground plane; for the large scale field tests, the pool is constructed below the ground level). In fact, the fuel tanks are usually built with its top at certain height above the ground. Meanwhile, there is still no work reported concerning the pool height effect

Table 1
Summary of previous experiments and correlations.

Literatures	Formula	Fuel	Wind speed (m/s)	Pool diameters (m)
Welker and Sliepcevich [14]	$\frac{D+L_{drag}}{D} = 2.1Fr_w^{0.21}\left(\frac{\rho_v}{\rho_a}\right)^{0.48}$	Methanol Acetone *n*-Hexane Cyclohexane benzene	0.3–2.0	0.1–0.61
Raj [15]	$\frac{L_{drag}}{D} = 2.375\left(\frac{\rho_v}{\rho_a}-1\right)^{0.5}Fr_w^{0.5}$	Data from experiment of Welker and Sliepcevich [14]		
Moorhouse [16]	$\frac{D+L_{drag}}{D} = 1.6Fr_{w,10m}^{0.061}$ Conical flame representation $\frac{D+L_{drag}}{D} = 1.5Fr_{w,10m}^{0.069}$ Cylindrical flame representation	LNG	1.8–14.4	6.9 9.7 10.9 13.75 15.4
Johnson [18]	$\frac{D+L_{drag}}{D} = 1.49Fr_{w,10m}^{0.0845}$	Data from Nedelka et al. [17]		
		LNG	1.5–13.5	1.8, 6.1, 10.6, 12.2, 20, 35
Mudan [19]	$\frac{D+L_{drag}}{D} = Fr_{w,10m}^{0.069}\left(\frac{\rho_v}{\rho_a}\right)^{0.48}$	Combined the correlations of Welker and Sliepcevich [14] and Moorhouse [16]		
Lautkaski [20]	$\frac{D+L_{drag}}{D} = 1.2Fr_{w,10m}^{0.069}\left(\frac{\rho_v}{\rho_a}\right)^{0.48}$	LNG	6.15	20
		LPG	6.6	52
		Isohexane	8–20	
Raj [15]	$\frac{L_{drag}}{D} = \Gamma\left(\frac{U_w D}{v_a}\right)^{-0.25}Fr_{w,10m}^{0.5}$	Data from Welker and Sliepcevich [14] and Mudan [19]		
	$\Gamma = 25\left[\frac{w}{(1-w\rho_a/\rho_v)(\rho_a/\rho_v)^{1/2}}\right]^{1/2}$	Methanol LNG		7–35.7