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Flame length elongation behavior of medium hydrocarbon pool fires in cross air flow

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HIGHLIGHTS

- Flame length elongation behavior due to cross air flow revealed.
- A global model developed for enhancement of mass burning rate due to cross air flow.
- A generalized model proposed on elongated flame length (ℓ_f), in relation to an amended Froude number.

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ABSTRACT

This paper presents an experimental investigation on flame lengths of medium pool fires under horizontal cross air flows. Square pool fires with dimensions of 10 cm, 15 cm, 20 cm, and 25 cm, using ethanol and heptane as typical fuels, are burned under cross air flows ranged in 0–2.5 m/s. The burning rates are measured by an electronic balance with accuracy of 0.1 g. The flame geometrical characteristics are recorded by a CCD (Charge-Coupled Device) digital camera, in which the mean flame length is quantified based on flame appearance intermittency spatial distribution. Results show that the cross air flow enhances the mass burning rate in a linear function of flow speed. Such enhancement effect is more prominent, indicated by a higher enhancement rate (β), for heptane than that for ethanol. This fuel type effect on β can be accounted for by a thermochemical property-Heat Release Parameter of the fuel (R, ratio of heat of combustion to heat of effect evaporation, $R = \Delta H_c/\Delta H_{fg}$). The normalized value of β/R is in a linear function of reciprocal of pool length ($\beta/R \sim d^{-1}$) and independent of fuel. The flame length is found to be elongated by the cross air flow due to the enhancement of the fuel burning (evaporation), as also being more remarkable for heptane than ethanol. A generalized model (Eq. (18)) is proposed to approximate the elongated flame length (ℓ_f), in relation to an amended dimensionless Froude number of $\frac{u}{\sqrt{gd}} \cdot \frac{s\Delta H_c}{M_{\text{fuel}}\Delta H_{fg}} \cdot \frac{M_{o_2}}{\rho_a Y_{o_2,\infty}}$, as incorporating globally both the thermochemical property (represented by R parameter, $\frac{\Delta H_c}{\Delta H_{fg}}$), molecular property and reaction molar stoichiometric ratio (represented by $\frac{s}{M_{\text{fuel}}}$) of the fuel, as well as the ambient oxygen molar concentration factor (represented by $\frac{M_{o_2}}{\rho_a Y_{o_2,\infty}}$).

1. Introduction

Hydrocarbon pool fire behavior, as an important fundamental topic in fire and combustion research [1–3], has been studied for decades. In no wind condition, for "small" pool fires in the laminar flame flow regime, for example less than 0.1 m, the conductive heat supply down through the rim walls is dominant, thus its burning rate (per unit surface area, mass burning flux) decreases with increase in pool size. Thermal radiation feedback from flame to the fuel surface begins to be more and more important in the transition flame flow regime as pool fire size beyond 0.1 m, leading to an increment of burning mass flux with pool size in the "medium" size transitional regime where the dominant heat supply transfers from convection to radiation; and finally approaching an asymptotic value for "large" pool fires in the fully turbulent flame flow regime where the flame radiation feedback is overwhelmingly predominant. However, when subjected to a cross air flow, the radiation feedback will decline considerably due the deflection of the flame and the convection will play important role and even predominant [4]. The flame geometrical characteristics, including height (length), shape, etc,. are dominant factors in calculation of its radiation emission hazard [5–10].

The flame geometry of a pool fire has been investigated extensively in early years, but mainly in a quiescent ambient air condition. Under a quiescent condition, the flame shapes straight

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Nomenclature

c_l	specific heat of the fuel, kJ/kg K
C_p	specific heat of air, kJ/kg K
D	pool fire side dimension (square), m
D	fire source diameter, m
G	gravity acceleration, 9.8 m/s^2
H	flame height, m
h_{fg}	latent heat of evaporation, kJ/kg
ΔH_c	heat of combustion of the fuel, kJ/kg
ΔH_{fg}	effective heat of evaporation, $\Delta H_{fg} = h_{fg} + c_l(T_{\text{boil}} - T_a)$, kJ/kg
ℓ_f	flame length, m
$\dot{m}''$	fuel mass burning rate per unit area (mass flux), kg/m^2 s
M	molecular weight
$\dot{Q}$	heat release rate, kW
$\dot{Q}^*$	dimensionless heat release rate, $\dot{Q}^* = \frac{\dot{Q}}{\rho_a c_p T_a \sqrt{gD}D^2}$
R	fuel thermochemical property Heat Release Parameter, $R = \Delta H_c/\Delta H_{fg}$
R_i	Richardson number
S	molar stoichiometric oxygen to fuel ratio (3 for ethanol and 11 for heptane)
T_a	ambient temperature, K
T_{boil}	boil point of the fuel, K
T_f	flame temperature, K
u	cross air flow speed, m/s
u^*	dimensionless cross air flow speed, $u^* = \frac{u}{(g\dot{m}''D/\rho_a)^{1/3}}$
$Y_{o_2,\infty}$	oxygen mass percentage concentration in ambient air

Greek symbols

ρ_a	density of air, kg/m^3
θ	flame tilt angle from vertical
β	burning rate enhancement rate due to cross air flow
λ	flame elongation coefficient, 2.48

vertically that the flame height is the most important dimension in characterizing the flame geometry. Thomas [11] has correlated the laboratory experimental data to determine the flame height of wood crib fires based on its burning rate and fire source diameter. Heskestad [12,13] has proposed the following widely adopted non-dimensional equation for estimation of the flame height, based on correlation of data for a wide variety of fire sources including pool fires,

$$\frac{H}{D} = 3.7\dot{Q}^{*2/5} - 1.02 \tag{1}$$

where H is flame height, D is fire source diameter and $\dot{Q}^*$ is dimensionless heat release rate,

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_a c_p T_a \sqrt{gD}D^2} \tag{2}$$

Under a horizontal cross air flow (wind) condition, the flame will be deflected by the flow to tilt with an angle from vertical. This will make the radiation intensity to the downstream position to be stronger. The current studies on pool fire burning behaviors under cross air flow condition are still relative lacking. The relatively limited investigations on this topic reported in the literatures are mostly concerning the effect of cross air flow on the burning rate of a hydrocarbon pool fire [2,14–20]. The equations available to characterize the flame length under a cross air flow in the literatures seem to be still mainly relied on the early works [11,21]

$$\frac{\ell_f}{D} = a \cdot \left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{\eta} \cdot u^{*b} \tag{3}$$

where $\dot{m}''$ is the fuel mass burning rate per unit area (mass flux) with no cross air flow, u^* is the dimensionless cross air flow speed,

$$u^* = \frac{u}{(g\dot{m}''D/\rho_a)^{1/3}} \tag{4}$$

the constant a, b and η were empirically correlated to be 55, −0.21 and 0.67 by Thomas based on wood crib fire [11], and 62, −0.044 and 0.254 by Moorhouse based on LNG fire [21].

However, it should be noted that the current correlation concerning cross air flow effect on flame length are not generally for hydrocarbon pool fires. A fact is that all these correlations do not include the effect of cross air flow on the burning rate of the fire. The effect of cross air flow on burning behavior of wood crib fires and LNG fires is expected to be different from that of a hydrocarbon pool fire. It has been reported [17–20] that the burning rate of a pool fire will be considerably enhanced by the cross air flow in a linear function, in which the enhancement rate (β, increment of burning rate with cross air flow speed) is proportional to the reciprocal value of the characteristic length of the pool [20]. The burning rate determines the fuel evaporation rate, which in turn certainly dominates the flame length. So, the flame length of a hydrocarbon pool fire under a cross air flow condition needs to be further quantified. The effect of cross air flow on the burning rate should be included into the prediction models for the flame length of a pool fire.

A series of experiments are then conducted in this paper to investigate pool fire flame length subjected to a horizontal cross air flow. The goal is to advance the current knowledge on pool fire behavior under a cross air flow by following attempts:

(1) The variation of burning rate with cross air flow speed is further correlated based on the earlier works [20] for definitely different fuels, ethanol and heptane. This is to include fuel type effect factor into the current model for a general relation applicable for different fuels, and to form a base for a further correlation on flame length.
(2) A mathematical method is brought forward to estimate the mean flame length in a cross air flow. A new general model for flame length is developed, which incorporates globally the effect of cross air flow on the burning rate, the fuel type effect and ambient oxygen concentration condition.

For the above attempts, it has been found that the hydrocarbon pool fire flame length elongated remarkably by the cross air flow. The flame length are correlated quantitatively with cross air flow speed and fuel type parameters including altogether non-dimensionally in general the thermochemical property (R parameter defined as $\Delta H_c/\Delta H_{fg}$), molecule weight, and reaction molar stoichiometric ratio of oxygen to fuel.

Following this introduction, there are three more sections. The Section 2 introduces the experimental facility, measurement setup and conditions. The Section 3 includes the experimental results and correlations of burning rate and flame length. The last section summarizes the major findings and conclusions of the paper.

2. Experimental

2.1. Experimental setup

The experimental setup has been presented in details in [4,22]. The overall schematic view of the experimental setup is shown in