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Wind-blown pool fire, Part II: Comparison of measured flame geometry with semi-empirical correlations

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ABSTRACT

Experimental measurements of flame drag, flame tilt and flame length, which were obtained for 2 m diameter Jet A fires in crosswinds of 3–10 m/s and described in Part I of this paper, were compared to values predicted using published semi-empirical correlations. Results were shown to be influenced in part by differences in the method used to measure flame geometry and in the boundary conditions between different experiments. Flame tilt values were predicted most successfully by correlations involving a combination of the Froude number U^2/gD and the non-dimensionalized heat release rate Q^*. Values estimated using similar correlations for flame drag and flame length were less successful, indicating gaps in the relevant physics modeled by those correlations. Fuel vapor density played an important role in determining the extent of flame drag. At high wind speeds, the horizontal momentum of the wind dominated over buoyancy effects in producing flame drag, physical effects not necessarily captured in the existing correlations. Flame length appeared to be governed by factors such as fuel vapor density and heat of combustion of the fuel, as well as wind speed and fuel burning rate. The restriction in air entrainment under conditions of large flame drag greatly increased flame length, particularly at high wind speeds, and should also be considered in future correlations.

1. Introduction

Research into wind-blown pool fires has largely focused on parameters that describe flame geometry, particularly those needed to estimate radiative heat transfer and thermal hazard from the fire [1–5]. In most previous studies, flame geometry has been characterized using photographic or video images of the fire, but such methods can be limited in large hydrocarbon fires where significant smoke blockage of the luminous flame envelope occurs. Part I of this two-part paper showed that more detailed characterization of the flame geometry can be made using the temperature field in the fire plume [6]. In this part, values for flame drag, flame tilt angle and flame length obtained based on the temperature data are compared to values predicted using semi-empirical correlations available in the literature. First, published correlations for predicting flame drag, tilt and length are reviewed and then applied to the present situation to predict the flame geometry. Results are compared to measured data to determine sources of discrepancy and thereby identify gaps in the physics modeled by the correlations.

2. Literature review

2.1. Flame drag correlations

As part of the overall characterization of wind-blown flame geometry, flame drag, or trailing of the flame along the ground beyond the downwind edge of the fuel pool, has been examined in several studies [7–10]. Typically, flame drag is expected to occur when the density of the fuel vapors is greater than that of the surrounding air, causing the vapors to remain near the ground until they are heated sufficiently to rise due to buoyancy, then entrain and mix with surrounding air [7,8]. The air–vapor mixture burns as a diffusion flame along the outer edges of the plume and thus the flame appears to trail beyond the downwind edge of the fuel source. Although the above physical description of flame drag is expected to apply for relatively low wind speeds, flame drag at much higher wind speeds is likely extended due to the horizontal momentum of the wind overcoming buoyancy of the hot fire gases and pushing them closer to the ground.

To date, several attempts have been made to correlate experimental flame drag data with wind speed, as shown in Table 1. Eq. (1) was based on visual data taken in small to medium hydrocarbon fires, while Eqs. (2) and (3) were based on visual data taken in large liquid natural gas (LNG) fires. All three equations were obtained through least squares' fits to experimental data

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Nomenclature

Γ	constant dependent on fuel properties in Eq. (6)
μ_a	viscosity of ambient air (kg/m/s)
ρ_a	density of ambient air (kg/m^3)
ρ_g	density of fuel vapors at boiling point (kg/m^3)
θ	flame tilt angle (deg)
c_f	specific heat of liquid fuel (J/kg/K)
c_{pa}	specific heat of air at constant pressure (J/kg/K)
D	diameter of fuel pool (m)
D'	length of elongated flame base when flame drag is present (m)
Fr	Froude number, U^2/gD
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of evaporation (J/kg)
ΔH_c	heat of combustion (lower value) of fuel in air (J/kg)
ΔH_{fg}	effective heat of evaporation, $\Delta H_{fg} = h_{fg} + c_f(T_{bp} - T_a)$ (J/kg)
L	flame length (m)
L_0	flame length in still air (m)
M_{fuel}	molecular weight of fuel (kg/mol)
M_{O_2}	molecular weight of oxygen (kg/mol)
$\dot{m}''$	mass burning rate per unit area of fuel (kg/m^{2}s)
$\dot{Q}$	heat release rate (W)
Q^*	non-dimensionalized heat release rate, $\dot{Q}/(\rho_a c_{pa} T_a \sqrt{gD}\, D^2)$
Re_D	Reynolds number, $UD\rho_a/\mu_a$
s	molar stoichiometric oxygen-to-fuel ratio
T_a	temperature of ambient air (K)
T_{bp}	boiling point of fuel (K)
T_f	flame temperature (K)
U	wind speed (m/s)
U_c	minimum wind speed required for flame tilt to occur, $(g\dot{m}''D/\rho_a)^{1/3}$ (m/s)
$U_{c,mod}$	minimum wind speed required for flame tilt to occur, $(g\dot{m}''D/\rho_g)^{1/3}$ (m/s)
Y_{O_2}	mass percentage concentration of oxygen in ambient air

Table 1
Summary of flame drag correlations.

Eq.	Correlation	Wind speed	Burner size	Fuel	Ref.
(1)[a]	$\frac{D'}{D} = 2.1Fr^{0.21}\left(\frac{\rho_g}{\rho_a}\right)^{0.48}$	0.2–2.1 m/s	0.1–0.6 m diameter	Acetone, benzene, methanol, n-hexane, cyclohexane	[7,10]
Conical flame representation (Eq. (2))					
(2)	$\frac{D'}{D} = 1.6Fr^{0.061}$	1.8–14.4 m/s	6.1 m × 6.1 m to 15.2 m × 12.2 m	LNG	[2]
Cylindrical flame representation (Eq. (3))					
(3)	$\frac{D'}{D} = 1.5Fr^{0.069}$	1.8–14.4 m/s	6.1 m × 6.1 m to 15.2 m × 12.2 m	LNG	[2]
(4)[b]	$\frac{D'}{D} = Fr^{0.069}\left(\frac{\rho_g}{\rho_a}\right)^{0.48}$	Generalized correlation for hydrocarbon fires			[1]
(5)	$\frac{D'}{D} = 1.2Fr^{0.069}\left(\frac{\rho_g}{\rho_a}\right)^{0.48}$	Generalized correlation for hydrocarbon fires			[9]
(6)	$\frac{D'-D}{D} = \Gamma\, Re_D^{-0.25} Fr^{0.5}$ where $\Gamma = \Gamma(\Delta H_c, \rho_g/\rho_a)$	Generalized correlation for circular, liquid fuel pool fires			[8]

[a] The error in the sign of the exponent of the Froude number has been corrected.
[b] The error in the density fraction, which was inadvertently inverted by Mudan [1] when he misquoted Eq. (1), has been corrected.

within the ranges of wind speed, burner size and fuel type listed in the table. The general form of Eq. (1) was determined using dimensional analysis[2] [10], while Eqs. (2) and (3) were adapted specifically to fit the LNG data. As such, the fuel vapor-to-air density ratio was implicitly incorporated into the constant coefficient. Eq. (4) was subsequently proposed as a generalized correlation for hydrocarbon fires and was obtained by combining (albeit without justification) Eqs. (1) and (3) [1]. Eq. (5) is a slightly modified version of Eq. (4), containing an additional coefficient to account for the vapor density of LNG and allow Eq. (4) to match Eq. (3) for that particular fuel [9]. Finally, Eq. (6) is a generalized correlation for circular pool fires that was derived from a physical model of flame drag. The model took into account not only wind speed, fire size and fuel vapor density, but also the rate of heat release from the fire, which affects the buoyancy of the burnt gases. The vapor density and heat of combustion of the fuel (along with other entrainment parameters related to stoichiometric combustion) were used to determine the value of the fuel property constant Γ in Eq. (6) [8].

In the study of Lautkaski [9], the author did not find evidence of increasing flame drag with increasing fuel vapor density in the range $1.6 \le \rho_g/\rho_a \le 2.7$, in contrast to the trend suggested by Eqs. (4) and (5). Unlike other authors who thought that flame drag was caused primarily by the fuel vapors being denser than the surrounding air, Lautkaski [9] postulated that the extent of flame drag would be determined by a balance between the momentum of the wind-driven plume flow and the flow of air being entrained into the leeward side of the fire, in a direction opposite to the wind. Since this air entrainment is induced by the upward momentum of the buoyant flame gases, the density of the fuel vapors at the base of the fire would not be a controlling parameter in determining flame drag. Lautkaski [9] therefore suggested that the density ratio ρ_g/ρ_a be omitted from the correlations and recommended Eq. (3) as the most appropriate correlation for predicting flame drag in large hydrocarbon pool fires. On the other hand, in the physical model developed by Raj [8], the density ratio ρ_g/ρ_a was included as a key

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[2] In this analysis, the non-dimensionalized flame drag was found to depend on the fuel vapor-to-air density ratio, Froude number and Reynolds number, but the Reynolds number was thought to be less important than the other two parameters because it was least related to buoyancy [10].