Fuel 106 (2013) 730–736

Contents lists available at SciVerse ScienceDirect

Fuel

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

A new mathematical quantification of wind-blown flame tilt angle of hydrocarbon pool fires with a new global correlation model

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HIGHLIGHTS

- A new mathematical methodology is brought forward to objectively quantify the hydrocarbon pool fire flame tilt angle in a wind.
- A new dimensionless global parameter is brought forward to collapse the flame tilt angle.
- The proposed new global model can better converge and correlate the measured data than previous models.

ARTICLE INFO

Article history:
Received 28 June 2012
Received in revised form 25 October 2012
Accepted 26 October 2012
Available online 10 December 2012

Keywords:
Flame tilt angle
Hydrocarbon pool fire
Ethanol
Heptane
Wind speed

ABSTRACT

A new mathematical methodology is brought forward in this paper to objectively quantify the flame tilt angle based on flame appearance intermittency spatial distribution obtained from the flame images series recorded in the experiments, in counteracting the uncertainty in traditional method due to the fact of extensive vibration nature of the flame in a wind. The flame tilt angle is determined based on a proposed sum function of the product of multiplication of $p(x, y)$ as probability of flame appearance at each pixel, by $D(x, y)$ as perpendicular distance from the pixel to a threshold line originated from the flame base center. The flame tilt angle is solved mathematically as the angle of the threshold line when the above sum function at the two sides of the threshold line in the flame intermittency distribution contour are early equal. Experiments are carried out for ethanol and heptane square pool fires with dimensions of 10 cm, 15 cm, 20 cm and 25 cm in wind speed of 0–2.5 m/s. The tilt angles of the flames in the experiments determined by above mathematical method are compared with previous models reported in the literatures. A new dimensionless global parameter, equating the wind speed by a characteristic uprising velocity of the flame supported by the buoyancy strength of the pool fire, is further proposed, which is shown to better converge and correlate the flame tilt angle data than previous models.

1. Introduction

Hydrocarbon pool fire behavior, an important fundamental topic in fire and combustion research [1–3], has been studied for decades. The flame geometrical characteristics, including height, shape etc. are dominant factors in determination of its radiation emission hazards [4–12]. Under a wind condition, the flame will be blown to tilt with an angle from the vertical direction. This increases the radiation intensity to the downstream area, which is crucial in fire spread. So, the flame tilt angle of a hydrocarbon pool fire in a wind is an important parameter.

Models for flame tilt angles have been based on correlations of experimental observations. Many of the available equations in the literatures rely on the early correlation by Thomas [10] of experimental data obtained from two-dimensional wood crib fires [10],

$$\cos(\theta) = 0.7u^{*-0.49} \tag{1a}$$

where u^* is the dimensionless wind speed given by

$$u^* = \frac{u}{(g\dot{m}''D/\rho_\infty)^{1/3}} \tag{2}$$

Eq. (1a) is further amended by American Gas Association (AGA) as follows [12,13]:

$$\cos(\theta) = \begin{cases} 1 & \text{for } u^* \leqslant 1 \\ 1/\sqrt{u^*} & \text{for } u^* > 1 \end{cases} \tag{1b}$$

There are also many studies in the literatures, which correlate the tangent value of the flame tilt angle, $\tan(\theta)$ (or $[\tan(\theta)/\cos(\theta)]$, however in this form, the factor of $\cos(\theta)$ is usually finally omitted), by the dimensionless Froude number (Fr, u^2/gd, or $\frac{u}{\sqrt{gd}}$), in the form of

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0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2012.10.075

Nomenclature

C_p	specific heat of air, kJ/kg K
d	pool fire size (square), m
D	fire source diameter, m
$D(x,y)$	perpendicular distance from pixel point (x,y) to the threshold line
g	gravity acceleration, 9.8 m/s^2
ΔH_c	heat of combustion of the fuel, kJ/kg
ℓ_f	flame height, m
$\dot{m}''$	fuel mass burning rate per unit area (mass flux), kg/m^{2}s
$p(x,y)$	flame appearance probability at pixel point (x,y)
R_i	Richardson number
T_0	ambient temperature, K
T_f	flame temperature, K
U	wind speed, m/s
u^*	dimensionless wind speed, $u^* = \frac{u}{(g\dot{m}''D/\rho_\infty)^{1/3}}$
v	characteristic flame vertical buoyant velocity supported by fire buoyancy strength

Greek symbols

ρ_∞	ambient air density, kg/m^3
θ	flame tilt angle from vertical
δ	flame width, m

$$\tan(\theta) = C \cdot Fr^b \quad (3)$$

Different values are suggested in the literatures for the power value (b) of Fr number (u^2/gd) of 1 (e.g. [14,15]), 0.8 (e.g. [16]), or 3/8 (e.g. [17]) by using natural gas diffusion flames.

However, it should be noted that these correlations are not generally for hydrocarbon pool fires. A fact is that all these correlations do not include the mass burning rate of the fire in a wind (mass burning rate in no wind used in Eq. (1a); or the mass burning rate is not even included in Eq. (3)). The effect of wind on burning behavior of wood crib fires and Liquefied Natural Gas (LNG) fires is expected to be different from that of a hydrocarbon pool fire. It has been reported [18–22] that the mass burning rate of a pool fire will be considerably enhanced by the wind. The mass burning rate determines buoyancy strength of the fire, which in competition to inertial of the wind, in turn dominates the flame tilt angle. So, the flame tilt angle of a hydrocarbon pool fire in a wind needs to be further quantified. The mass burning rate of the pool fire in a wind should be included into the flame tilt angle model.

Another fact is that the successful correlation of a model from the experiments is relied on the accurate determination of the flame tilt angle values of the hydrocarbon pool fires in a wind. However, due to the fluctuating nature of the flames, measurements of flame tilt angle are somewhat uncertain and difficult to be quantified accurately as the flame envelope is quite variable both spatially and with time. This brings uncontrollable uncertainty and makes the values somewhat subjective, based on visual observation, in the previous works.

To resolve above issues, a series of experiments are conducted in this paper to quantify the pool fire flame tilt angle in a wind with simultaneous mass burning rate measurement. A new and more objective mathematical method is brought forward to quantify the flame tilt angle in the experiments. A new dimensionless parameter representing the ratio of the inertial of the wind to the buoyancy of the flame supported by the buoyancy strength of the pool fire, is further proposed to collapse the flame tilt angle data. A new global model is non-dimensionally correlated in general to include wind speed, pool dimensions and mass burning rates of the pool fires.

Following this introduction, there are four more sections. The second section introduces the experimental facility, measurement setup and conditions. The third section includes the mathematical method to quantify the flame tilt angle from the flame image series recorded by the CCD (Charge-Coupled Device) camera. The fourth section presents the experimental results, collapse of the experimental data by previous models as well as by the new one proposed in this work. The last section summarizes the major findings and conclusions.

2. Experimental

Experiments are carried out in a wind tunnel as shown schematically in Fig. 1. The wind tunnel has a cross section of 1.5 m wide and 1.3 m high, with total length of 72 m to ensure the flow to be one-dimensional when full developed. Concerning the relatively small size of the wind tunnel cross section and so that its constraint effect on the burning and flame behavior of the pool fire if it is positioned inside the tunnel, the pool fire is positioned just downstream of the tunnel at a distance of 0.3 m. There is a horizontal platform at the outlet portal of the tunnel with its height flush with the tunnel floor. The pool fire is placed at the center of the platform with its bottom raised above the floor. The upstream wind flow speed when flowing out of the portal is monitored by a four-probe hotwire anemometer. The maximum wind speed considered in the experiments is about 2.5–3.0 m/s, based on the critical dimensionless Richardson number (R_i) $R_i = (1 - T_\infty/T_f)gd/u^2$ determined from the observations in former experiments [19,22], to reach the condition that the flame is deflected by the wind to be nearly attaching to the ground level with a tilt angle of almost 90°.

The pool fire sources are squared with dimensions of 10 cm, 15 cm, 20 cm and 25 cm, whose inner depth is 3.0 cm. The fuel surface level is maintained in the experiments at 2.6 cm above the bottom of the pool with a constant freeboard or lip height of 0.4 cm. A method similar to that of Rasbash et al. [23] is used to maintain the fuel layer depth during the burning period. As shown in Fig. 1, the fuel supply and surface level maintaining device consists of three fuel storages. The fuel in the top storage (#1) flows into the middle one (#2) by gravity force. The middle fuel storage is connected to the bottom of the pool fire through a pipe with inner diameter of 32 mm. The fuel surface layer in the middle fuel storage is maintained to be flush with that in the pool fire with extra fuel automatically flowing into the bottom fuel storage (#3). The total mass of the device including all the fuel in the three storages is measured by an electronic balance with resolution of 0.1 g. The electronic balance is connected to a computer, which automatically records the total mass with sampling intervals of 2 s. The experiments are repeated four times for each pool size under each wind speed, which shows good repeatability.

A CCD Camera of 3,000,000 pixels is positioned beside the pool fire to record the flame geometry characteristics (side-view). The film speed is 25 frames per second. The background wall is covered by black masking paper to avoid reflection of any optical noise.

3. A mathematical method for quantification of flame tilt angle

Here, a new more objective mathematical method is brought forward based on flame intermittency analysis, to quantitatively