Combustion and Flame 176 (2017) 370–376

Contents lists available at ScienceDirect

Combustion and Flame

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

Flame projection distance of horizontally oriented buoyant turbulent rectangular jet fires

Xiaolei Zhang[a], Longhua Hu[a,*], Xiaochun Zhang[b], Fei Tang[c], Yong Jiang[a,*], Yujie Lin[a]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] Faculty of Environmental Science and Engineering, Guangdong University of Technology, Guangzhou, China
[c] School of Transportation Engineering, Hefei University of Technology, Hefei, Anhui 230009, China

ARTICLE INFO

Article history:
Received 21 April 2016
Revised 7 July 2016
Accepted 22 October 2016
Available online 8 December 2016

Keywords:
Flame projection distance
Rectangular source
Horizontally oriented jet fire
Characteristic length scale
Aspect ratio

ABSTRACT

This paper investigated the flame projection distance (defined as the distance from the nozzle exit to the furthest point of the flame in the horizontal direction) of horizontally oriented buoyant turbulent rectangular jet fires. The experiments as well as the correlations reported previously were limited for axi-symmetrical fire sources that are not applicable for non-axi-symmetrical sources. In this work, experiments were conducted using horizontally oriented rectangular nozzles with aspect ratio, n (nozzle length to nozzle width: $n = L/W$), varied from 1:1 to 71:1 covering the axi-symmetrical, rectangular and linear sources, employing propane as fuel. Results showed that the flame projection distance increased with the heat release rate growth. At the same time, the flame projection distance decreased with the increase of the aspect ratio n for a given nozzle exit area. A non-dimensional function was then derived for the projection distance, in which a characteristic length scale was found in relation to the nozzle length and width, based on the balance of the momentum flux to the buoyancy flux of the projected flame. A new non-dimensional heat release rate was defined based on the proposed characteristic length scale. The data obtained in this work for different aspect ratios, as well as those reported previously for axi-symmetrical sources, were shown to be well correlated by the derived function in two regimes: (1) for relative small non-dimensional heat release rates, the flame projection distance has a 2/3 power dependency on the heat release rate as for a 2-D trend fire; (2) for relative large non-dimensional heat release rates, the flame projection distance has a 2/5 power dependency on the heat release rate as for a 3-D trend fire. The proposed new correlation provides a more general and practical base for estimating the projection distance of horizontally oriented buoyant turbulent jet diffusion flames.

1. Introduction

A horizontally oriented projected flame would occur when the fire is resulted from a leakage at the side surface of a gas fuel pipe. Considering the high risk of directly igniting the combustible nearby in the horizontal direction by the flame, its projection distance (ℓ_p) (the horizontal distance from the nozzle exit to the furthest point of the flame) is a crucial parameter to be quantified [1–11]. However, the measured data as well as studies on horizontally oriented jet diffusion flames are still very limited as reviewed below.

The jet diffusion flame can be buoyancy-driven ($Fr_f < 5$) or momentum-driven ($Fr_f \geq 5$), determined by the flame Froude number ($Fr_f = \frac{u_0}{(gd)^{1/2}(S+1)^{3/2}(\rho_0/\rho_\infty)^{1/4}(\overline{\Delta T_{f,a}}/T_\infty)^{1/2}}$ [12,13]. Becker and Liang [1] did the dimensional analysis on horizontally oriented buoyancy-driven and momentum-driven jet flames (for example: $0.76 < Fr_f < 14.41$ for methane) of round fire source, in which the flame projection distance (ℓ_p) and the flame vertical height ($H_{vertical}$) were related by

$$H_{vertical}/\ell_0 = fcn\left(\xi_L, \ell_p/\ell_0\right) \tag{1}$$

where ξ_L is the non-dimensional length scale (or non-dimensional flame height ℓ_0) defined by

$$\xi_L = \left(\pi g \rho_\infty \ell_0^3/4G_0\right)^{1/3} \tag{2}$$

in which g is the acceleration of gravity, ρ_∞ is ambient air density, G_0 is the fuel momentum flux at the jet exit defined as $G_0 = \dot{m}_0 u_0$, ℓ_0 is the flame height produced by the vertical oriented burner. In their study, the flame projection distance was photographed and determined by the time-averaged view (1 s of exposure time). Gore and Jian [2] measured the flame projection distance of horizontally oriented buoyancy-driven jet flames ($0.3 < Fr_f < 0.9$) produced by

---

[*] Corresponding authors. Fax: +86 551 63601669.
E-mail addresses: hlh@ustc.edu.cn (L. Hu), yjjiang@ustc.edu.cn (Y. Jiang).

http://dx.doi.org/10.1016/j.combustflame.2016.10.016

Nomenclature

c_p	specific heat of air at constant pressure (kJ kg^{-1} K^{-1})
d	nozzle diameter (m)
Fr	Froude number
Fr_f	flame Froude number
g	gravitational acceleration (m s^{-2})
G_0	jet momentum flux (kg m s^{-2})
$H_{vertical}$	vertical projected flame height (horizontal burner orientation) (m)
J_0	buoyancy flow flux (kg m s^{-3})
L	nozzle length (m)
$\dot{m}_0$	fuel mass flow rate at exit (kg s^{-1})
$\dot{m}_f$	mass flow rate of the flame flow (kg s^{-1})
n	aspect ratio L/W
$\dot{Q}$	heat release rate (kW)
$\dot{Q}'_L$	heat release rates per unit length (kW/m)
$\dot{Q}^*$	non-dimensional heat release rate $\dot{Q}^* = \frac{\dot{Q}}{c_p\rho_\infty T_\infty\sqrt{g}W^{3/2}L}$
$\dot{Q}^*_d$	non-dimensional heat release rate $\frac{\dot{Q}}{\rho_\infty c_p T_\infty\sqrt{g}d^{5/2}}$
$\dot{Q}^*_{\zeta_\ell}$	non-dimensional heat release rate (Eq. (18))
Re	Reynolds number
s	nozzle exit area (m^2)
S	air to fuel mass stoichiometric ratio
T_f	flame temperature (K)
T_∞	ambient air temperature (K)
$\Delta T_{f,a}$	mean flame temperature rise (K)
u_0	fuel flow velocity (m s^{-1})
u_f	characteristic flame travelling velocity (m s^{-1})
W	nozzle width (m)

Greek symbols

α	empirical constant
ℓ_0	flame height (vertical burner orientation) (m)
ℓ_p	flame projection distance (m)
ρ_0	density of the fuel (kg m^{-3})
ρ_f ρ_∞	flame density (kg m^{-3}) ambient air density (kg m^{-3})
ζ_ℓ	characteristic length scale (m) (Eq. (18))
κ	empirical coefficient
ξ_L	non-dimensional length scale $\xi_L = (\pi g\rho_\infty\ell_0^3/4G_0)^{1/3}$
Π	non-dimensional variable defined according to Eq. (20)

Subscripts

f	flame
∞	ambient conditions
0	fuel

round source from 30 representative images, and made a comparison of their data with [1]. Peters et al. [3] numerically studied the flame projection distance of horizontally oriented jet flames for various Froude numbers. Based on the study in [3], Gore and Jian [4] proposed an analytical solution for flame trajectories.

Recently, Smith et al. [5,6] studied the flame size of horizontally oriented buoyancy-driven to momentum-driven jet flames ($0.71 < Fr_f < 4.47$; however, one test of $Fr_f = 4.47$ was taken as momentum-driven in [5,6]) produced by circular and elliptic burners. A digital video camera with a shutter speed of 1/100 s was used to take flame photographs and 4 images were used to obtain the average flame projection distance. Johnson et al. [7] studied some large scale horizontally released natural gas jet flames with a wind effect. The measured mean flame shape was derived in the study by superimposing the instantaneous flame shapes from every video frame during an averaging period of 10–20 s. Some works about the flame projection distance of horizontal hydrogen jet fires were reported in [8–10]. In [8], the flame projection distance of momentum-driven hydrogen jet flames ($Fr_f > 8$) obtained from 90 successive video camera frames with an interval of 1/30 s during a period of 20–23 s was expressed as a function of the fuel mass flow rate ($\dot{m}_0$)

$$\ell_p = 19.9\dot{m}_0^{0.51} \tag{3}$$

In [10], some large scale buoyancy-driven ($0.59 < Fr_f < 0.92$) [12,13] experiments were conducted using round fire source and the flame projection distance was determined by analysis of video frames during a period of 30–60 s. The flame projection distance was correlated empirically in the study with fire heat release rate ($\dot{Q}$)

$$\ell_p = 2.8893\dot{Q}^{0.3728} \tag{4}$$

Mogi et al. [11] studied the flame projection distance of both buoyancy-driven and momentum-driven round liquefied dimethyl ether fire ($0.77 < Fr_f < 304.49$) [12,13] which was obtained from infrared images obtained from 30 successive frames with an interval of 1/30 s, and they proposed following non-dimensional correlation

$$\ell_p/d = 0.28\dot{Q}_d^{*0.53} \tag{5}$$

where $\dot{Q}^*_d$ is defined as $\dot{Q}^*_d = \frac{\dot{Q}}{c_p\rho_\infty T_\infty\sqrt{g}d^{5/2}}$, and d is source diameter, c_p is the specific heat of air at constant pressure, T_∞ is the ambient air temperature. It is noted that the agreement in Fig. 7 in [11] is not good as the data covers both, buoyancy-driven and momentum-driven fires. However, the HRR is non-dimensionalized as if it is a buoyancy-driven fire.

The previous works on horizontally oriented jet flames only concerned axi-symmetrical (round) burners. However, in reality it is more common to have non-axi-symmetrical sources practically (for example, the crack of the pipe line is more common to be rectangular or even linear). Even for a vertical jet, the flame height of a rectangular or a linear source has different scaling law from that produced by an axi-symmetrical one [14–16]. For a horizontally oriented buoyant jet fire, there is a more complex competition between the momentum and the buoyancy at the nozzle exit as they are in perpendicular orientations, in comparison to that of a vertical one for which the momentum and the buoyancy are both in the vertical direction. How the flame projection distance of a rectangular fire behaves with heat release rate (fuel discharge rate) as well as the nozzle dimensions (aspect ratio) has not been quantified yet, meanwhile it is more practically important.

In this work, a series of experiments were carried out to measure the flame projection distance of horizontally oriented buoyant turbulent rectangular jet fire of several aspect ratios. The nozzle length to nozzle width ratio, $n = L/W$, varied from 1:1 to 71:1 including the axi-symmetrical, rectangular and linear sources. A theory was derived, and a characteristic length scale was found as a function of nozzle length and width, based on the balance of the momentum flux to the buoyancy flux at the nozzle exit, to non-dimensionally correlate the measured data of this work for different source dimensions (aspect ratios), as well as those reported in previous works for axi-symmetrical sources.

2. Experiments

Figure 1 depicts the experimental facility and measurement setup. The designed exit dimensions L (length) × W (width) of six