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A new mathematical method for quantifying trajectory of buoyant line-source gaseous fuel jet diffusion flames in cross air flows

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ABSTRACT

The gas leakage from a gaseous fuel pipeline usually leads to a jet fire, which causes both enormous loss of energy and thermal threat to the surrounding objects. The potential wild fire risk is a significant issue and need to be paid sufficient attention. This paper investigates the vertical flame height, horizontal flame length and provides a new mathematical method to quantify the trajectory of the flame produced by a linear buoyant turbulent jet fire, which can be resulted in due to pipeline fuel leakage, in cross air flows. Experiments are carried out by a 2 mm (width) $*$ 142.5 mm (length) line-source nozzle employing propane as fuel. The velocities of cross air flows are ranged from 0 m/s to 2.5 m/s. It is found that the vertical flame height and horizontal flame length can be well predicted by initial momentum ratio (r) and Froude number (Fr). A simple and easily applied explicit mathematical method is proposed to predict the trajectory length based on circumference approximation. All these findings can contribute to both combustion science and providing guidance for the wild jet fire risk assessment.

1. Introduction

Gaseous fuel energies have extensive applications in both industrial manufacture and personal life, such as heating industry [1,2], combustion and explosion research [e.g. 3–7]. Both of the combustion performance and potential fire hazards have been attracted broad attentions [8,9]. A turbulent gaseous fuel jet flame can be generated due to the ignition of leaking gas in case of soil biodeterioration, chemical corrosion on pipe or relief valves broken and so on [10]. The corresponding jet flame can impose high thermal fluxes and serious adverse impacts to the surrounding objects [11]. However, seldom research about such fire accident has been conducted.

Most of scientific reports about jet fire behaviors focus on the combustion characteristics in a quiescent air [e.g. 12–14]. However, the gaseous energy fuels are often transported in pump line and will run through many wild lands inevitably. A wild jet fire will form if the gaseous fuel leaked from the extraventricular pipeline and its combustion behavior should be remarkably influenced by the ambient wind [15–18]. The cross air flow will enhance the turbulence of fire plume and significantly affect the flame shape. The exploration for such jet fire behaviors are important and can help us to handle wild fire risk assessment and management [19].

Suman and Krishnan [20] have carried out some researches about circular jet flows in cross air flow. They showed that the vertical flame height (jet direction), horizontal flame length (cross air flow direction) which are important to describe the flame shape, can be described by the momentum ratio (r) of fuel gas to cross air flow, defined as:

$$r = \left(\frac{\rho_s V_s^2}{\rho_0 V_0^2}\right)^{1/2} \tag{1}$$

where ρ_s, V_s is density and velocity of fuel jet. ρ_0, V_0 is the density and velocity of cross air flow. The flame trajectory length is another important parameter. The previous experimental studies have defined the jet trajectory using the local velocity maxima [21] or the local scalar concentration maxima [22]. It is noted that the definition of the trajectory using both of these techniques needs expensive experimental apparatus and this makes it difficult to apply. Normally, the pipeline leakage vent is usually long-narrow, forms a line-source jet fire rather than a circular one. However, the trajectory length of such line-source jet fire in cross air flow has not been quantified previously.

So, in this paper, experiments were carried out to investigate the vertical flame height and horizontal flame length for a line-source buoyant turbulent jet fire in cross air flows. A simple and

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Nomenclature

d_f	horizontal flame length (m)
D	characteristic length (m)
Fr	Froude number
Fr_f	flame Froude number
g	gravitational acceleration (kg·m/s^2)
H_f	flame height
r	initial momentum ratio
r^*	the equivalent length
L	length of linear burner (m)
P	ambient air pressure (Pa)
S	air to fuel mass stoichiometric ratio
T_0	cross air temperature (K)
V_0	cross air velocity (m/s)
V_s	initial gas velocity (m/s)
W	width of the linear burner (m)
$\overline{\Delta T}_f$	mean peak flame temperature rise (K)

Greek symbols

ρ_0	cross air density (kg/m^3)
ρ_s	fuel density at nozzle (kg/m^3)
ℓ_{traj}	trajectory length (m)
λ	parameter defined in Eq. (9)
θ	flame vertical included angle

Subscript

0	cross air flow
f	flame
s	gas fuel
traj	trajectory

easily applied mathematical method to present the trajectory is also proposed.

2. Experimental and mathematical method

2.1. Experimental

Fig. 1 depicts a schematic of the experimental facility and measurement setup. The designed linear nozzle's cross section is 2 mm (width) $*$ 142.5 mm (length). Propane with 99.99% purity is employed as gas fuel. A series of experimental scenarios with different mass flow rates (correspondingly discharge velocities) are carried out. The heat release rates are calculated based on the fuel mass flow rates by assuming completely combustion of fuel. Each case is repeated 3 times.

The cross air flow is produced by an axial flow fan and screened through a 72 m long tunnel. The cross air flow velocity is controlled by a frequency converter and monitored by a four-probe hot wire anemometer as shown in Fig. 1. The cross flow air velocities are ranged from 0 m/s to 2.5 m/s. The initial momentum ratios of gaseous fuel jet to cross air flow are ranged from 0.13 to 6.4.

The flame is visualized by a CCD (Charge-Coupled Device) camera of sensor size 8.5 mm with 3,000,000 pixels. The film speed of the camera is 25 frames per second. Time series images are disintegrated into discrete frames and processed one by one for each video record. Each image frame is firstly converted to gray scale image and then to binary image using the Otsu method [23,24]. Thousands of consecutive images are converted to binary images for statistical analysis. Flame intermittency contour (as shown later in Fig. 3) is then obtained by averaging the values of these consecutive binary images in each pixel position [24]. Then, the vertical flame heights and horizontal flame lengths can be obtained based on the averaged flame presence probability contour.

2.2. Mathematical method

Fig. 2 shows the definition of visible vertical flame height, horizontal flame length and flame vertical included angle. The flame vertical included angle θ is defined as angle formed by vertical direction and connecting line between burner source center and flame tip. It is observed that the flame shape of non-axisymmetrical linear jet fires in cross air flow here are more curved, which is different from the straight line proposed in the previous works conducted with axisymmetrical pool fires [25,26]. So, from phenomenological point of view, we proposed an arc curve to characterize the trajectory.

Fig. 3 shows four typical intermittency contours of flames with different jet fuel velocities and cross flow air velocities. The withe dots present the intermittency contour tips. It can be seen that the connection line of intermittency contour tips and fire source center, which are assumed to form the trajectory of flame in a cross air flow, can be considered as a portion of a circle. In a quiescent air, the trajectory can be deemed as a portion of an infinite circular correspondingly.

Fig. 4 shows a typical flame photo and trajectory based on circular assumption (fuel initial velocity V_s = 0.27 m/s, cross air velocity V_0 = 0.5 m/s). The center of circle is determined by intersection point of two blue dotted lines (perpendicular line of initial velocity direction at the position line source and vertical center line of chord length). In Fig. 4, V_t is the initial velocity, d_f is the horizontal flame length, α is half of central angle and H_f is the vertical flame length. We can calculate the parameters as following:

$$\theta = arccot\frac{H_f}{d_f} \tag{2}$$

$$\Theta = arccot\frac{V_0}{V_s} \tag{3}$$

So, the central angle (α) and radius (R) of circler is given by:

$$2\alpha = 2\left(\frac{\pi}{2} - \theta - \Theta\right) \tag{4a}$$

$$R = \frac{\frac{1}{2}\sqrt{H_f^2 + d_f^2}}{\sin\alpha} \tag{4b}$$

Then, the trajectory flame length can be calculate by

$$\ell_{traj} = \frac{2\alpha}{2\pi} * 2\pi R \tag{5a}$$

It can be expressed as following by subsuming Eq. (4) into Eq. (5a):

$$\ell_{traj} = 2\cdot\left(\frac{\pi}{2} - arccot\frac{H_f}{d_f} - arccot\frac{V_0}{V_s}\right) \cdot \frac{\frac{1}{2}\sqrt{H_f^2 + d_f^2}}{\sin\left(\frac{\pi}{2} - arccot\frac{H_f}{d_f} - arccot\frac{V_0}{V_s}\right)} \tag{5b}$$

The evolution of vertical flame heights (H_f) and horizontal lengths (d_f) in Eq. (5b) with cross air flow velocity will be correlated based on the experimental data and the results will be shown in Section 3.