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Non-dimensional correlations on flame height and axial temperature profile of a buoyant turbulent line-source jet fire plume

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Abstract

This article investigates flame height and axial temperature profile of a buoyant turbulent line-source jet fire plume. Previous correlations have been mainly for axi-symmetrical fire sources or linear pool-type (no initial momentum) fire sources. Experiments were carried out for this study using a 3 mm (width) $\times$ 95 mm (length) line-source nozzle with propane as the fuel. Flame heights and axial temperature profiles were measured for different heat release rates. It was found that the flame heights can be well correlated by flame Froude number with a 2/3 power function based on scaling analysis. A global non-dimensional four-regions correlation (continuous flame region, intermittent flame region, line-plume region, and axi-symmetric-plume region) is proposed to characterize the axial temperature profile of a line-source jet fire plume.

Keywords

Line-source buoyant turbulent jet fire, flame height, axial temperature profile, flame Froude number

Introduction

Gaseous fuels are often transported in pipelines at high pressure through energy supply networks.[1–4] A jet fire can form as a result of the leakage and ignition of hydrocarbon gaseous

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fuel in case of a broken pipe or safety valve, or similar accidental scenarios.[5] Jet fire can pose such serious adverse impact that its characteristics have received extensive research attentions[5–11] in the past decades.

Most of the past studies on jet fire plume characteristics are focused on axi-symmetric source condition. For example, Delichatsios[12] developed a dimensionless correlation for axi-symmetric flame height by a defined flame Froude number Fr_f to account for the transition from buoyancy to momentum-controlled jet flames[6,12,13] as well as for variations of mean flame temperature and turbulence

$$\frac{\ell_f}{(S+1)D(\rho_s/\rho_\infty)^{1/2}} = \frac{13.5Fr_f^{2/5}}{(1+0.07Fr_f^2)^{1/5}} \tag{1a}$$

where Fr_f is defined as

$$Fr_f = \frac{U_s}{(gD)^{1/2}(S+1)^{3/2}(\rho_s/\rho_\infty)^{1/4}(\overline{\Delta T}_f/T_\infty)^{1/2}} \tag{1b}$$

However, very limited works focus on the fire plumes induced by line fire source,[14–17] despite the fact that the non-axi-symmetric fire is more common than the axi-symmetric one, for example, fire due to gaseous fuel leakage from the fissure of the pipelines. Hasemi and Nishihata[15] proposed the following correlation to describe the visible flame heights of pool-type line-source propane fires

$$\ell_f = 0.035\dot{Q}_l'^{2/3} \tag{2}$$

where $\dot{Q}_l'$ is the heat release rate of the fire source per unit length. Meanwhile, Thomas[16] suggested the following correlation for line-source wood fires

$$\ell_f = 18.6R_l^{2/3} \tag{3}$$

where R_l is the mass burning rate per unit length.

One of the most comprehensive studies on fire plume of line-source fires has been reported by Yuan and Cox,[17] in which the visible flame heights and axial temperature profiles are quantified. Linear sand box is used as fire source to eliminate the initial momentum effect of the gaseous fuel, so as to produce a pure buoyant diffusive pool-type fire. Their proposed flame height correlation is similar to that of Hasemi ($\ell_f = 0.034\dot{Q}_l'^{2/3}$).[17] As for the axial temperature profile, they proposed

$$\Delta T = \kappa\left(Z/\dot{Q}_l'^{2/3}\right)^\eta \tag{4}$$

in which $\eta = -1$ is suggested for both the intermittent flame region and buoyant plume region. It is true that $\eta = -1$ for the buoyant plume region before it grows to be nearly axi-symmetrical one for a line-source fire. However, it is known that $\eta = -1$ for intermittent flame region is usually suggested for an axi-symmetrical fire source. In fact, how the axial temperature profile transits during the intermittent flame region to the buoyant plume region for a line-source jet fire is still not clear and needs to be quantified.

It is also noted that the above studies on line-source fire plume characteristic are mainly for pool-type fires, where the initial fuel momentum is nearly zero. For a jet fire, the initial momentum will affect entrainment, and thus, the flame heights and axial temperature profile, which has also not been addressed in the past. Therefore, this study addresses the above problems by following attempts:

1. The flame height of a line-source jet fire is quantified for different heat release rate (per unit source length). The correlation of Delichatsios[12] (equation (1)) for the axi-symmetrical source condition is further extended to the line-source jet fires;
2. The evolution of axial temperature profiles of a line-source jet fire plume is quantified with a global four-regions correlation proposed, based physically on the fact that transitioning development of axial temperature profile of a line-source jet fire plume should cover the continuous flame region, intermittent flame region, line-plume region, and finally, axi-symmetrical plume region.

Experimental

Figure 1 depicts a schematic of the experimental facility and measurement setup. The designed nozzle dimensions are 3 mm (width) $\times$ 95 mm (length). Propane is used as fuel. A series of experimental cases with different mass flow rates (correspondingly discharge velocities) are tested. Each case is repeated 3 times showing good repeatability.

The flame height is visualized by a charge-coupled device (CCD) 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 of images are decompressed into frames and processed one by one for each video record. Each image frame is first converted to gray scale image and then to binary image using the Otsu method.[18,19] More than 1000 consecutive images are converted to binary images for statistical analysis. Flame intermittency distribution is then obtained by averaging the values of these consecutive binary images in each pixel position.[20] This method provides a more objective quantification of the continuous flame height, mean flame height, and intermittent flame height than visual observations.

Axial centerline temperature profile along the flame and the buoyant plume is measured by K-type thermocouples (diameter of 0.5 mm) with measurement uncertainty estimated to be less than 1% or 3%. The measured temperature values by the thermocouples are calibrated by radiation loss correction based on the diameter of the thermocouple.[21,22]

Results and discussion

Flame heights

Figure 2 shows a typical intermittency contour of the averaged flame. The intermittency contour of the flame is obtained from the CCD camera as described in section "Experimental." Then, the continuous flame height (to intermittency = 0.95), mean flame height (to intermittency = 0.5), and intermittent flame height (or nearly visible flame tip) (to intermittency = 0.05)[23] can be quantified.

Figure 3 shows that the continuous flame height, mean flame height, and intermittent height can be well correlated by a 2/3 power of the heat release per unit length, as in common with previous reports.[1,15,16] However, the constants are different for these three flame

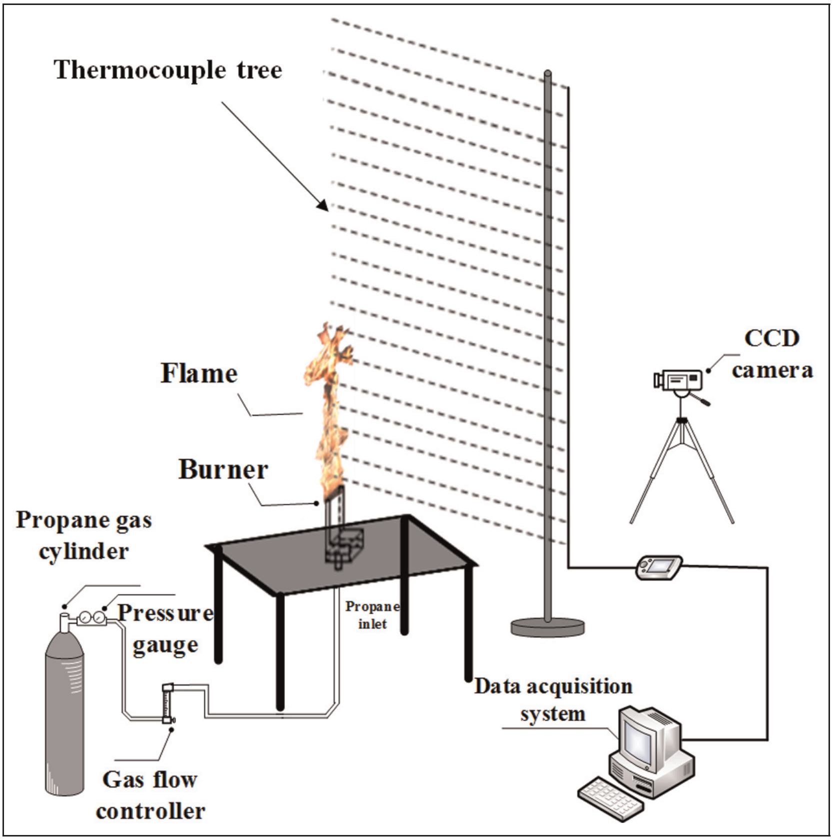

Figure 1. Experimental setup.
CCD: charge-coupled device.

heights, which has not been quantified before, especially for the continuous and mean flame heights. These correlations yield

$$\text{For continuous flame height } \ell_{f-c} = 0.0144\dot{Q}_l'^{2/3} \tag{5a}$$

$$\text{For mean flame height } \ell_{f-m} = 0.021\dot{Q}_l'^{2/3} \tag{5b}$$

$$\text{For intermittent flame height } \ell_{f-i} = 0.0287\dot{Q}_l'^{2/3} \tag{5c}$$

There is seldom correlation of continuous and mean flame height for a line fire, while some referable suggested values for the proportionality constant of intermittent flame height can be found from previous studies.[16,17] However, the proportionality constant for intermittent flame height proposed here (0.029) for line-source jet fires is smaller than that obtained by Thomas[16] with wood cribs fires and Yuan and Cox[17] with natural gas pool fires (0.034). This is due to the fact that the initial momentum of a jet fire enhances the air entrainment, which consequently implies that a relatively small distance (flame height) is needed to consume the gaseous fuel.

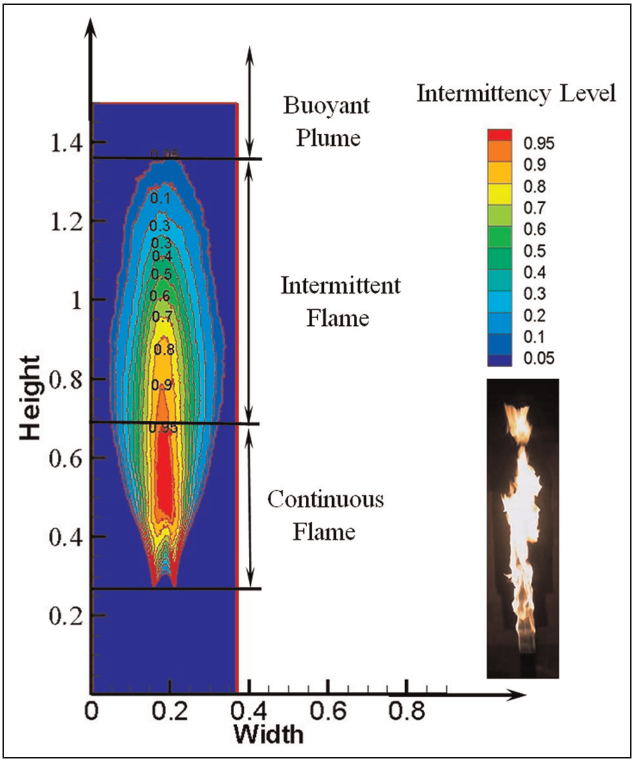

Figure 2. Continuous, mean, and intermittent flame height quantification based on flame intermittency contour ($\dot{Q} = 34.1$ kW).

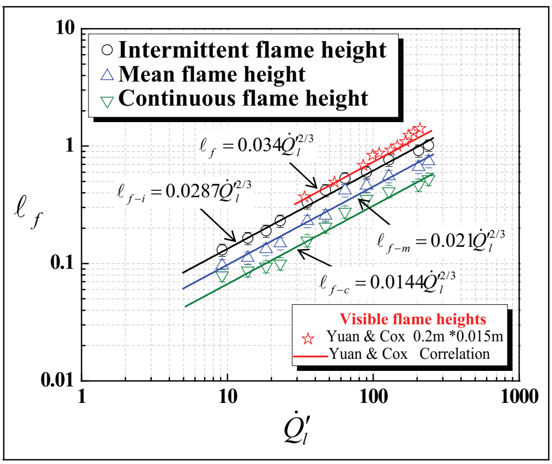

Figure 3. Correlation of flame heights against heat release rates.

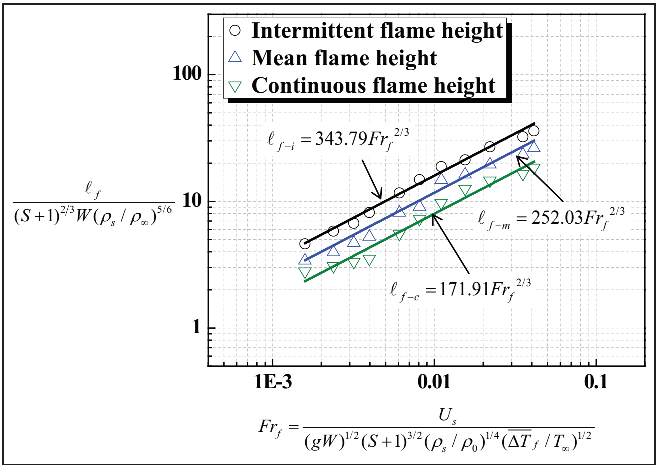

Figure 4. Non-dimensional correlation of flame heights against flame Froude number (Fr_f).

Then, we would like to account for such initial momentum effect for the line-source jet fire flame heights, by introducing the flame Froude number Fr_f (equation (1b)) proposed by Delichatsios[12] (meanwhile the nozzle width W is used as characteristic length, replacing the nozzle diameter as for an axi-symmetrical source).

The mean quantities of the flow should depend on the following global parameters, similar to that described in Delichatsios[6]

1. The mass flow rate per unit length at the nozzle normalized by ambient density

$$\dot{m}_l'/\rho_0 \tag{6a}$$

2. The effective buoyancy flow rate at the end of combustion

$$\left[\frac{\dot{Q}'_l(\chi_A - \chi_R)g}{(\rho_0 C_P T_\infty)}\right] \tag{6b}$$

Therefore, we can find a length scale similar to Delichatsios[12] using the above two parameters

$$\ell_p = \frac{\frac{\dot{m}'_l}{\rho_0}}{\left[\frac{\dot{Q}'_l(\chi_A - \chi_R)g}{(\rho_0 C_P T_\infty)}\right]^{1/3}} = W(1+S)^{2/3}\left(\frac{\rho_s}{\rho_0}\right)^{5/6} Fr_f^{2/3} \tag{6c}$$

Then, we can plot $\ell_f/((S+1)^{2/3} W(\rho_s/\rho_\infty)^{5/6})$ against Fr_f as shown in Figure 4. It can be seen that Fr_f can collapse the flame heights, satisfying the 2/3 power correlation by

$$\frac{\ell_f}{(S+1)^{2/3} W(\rho_s/\rho_\infty)^{5/6}} = \lambda Fr_f^{2/3} \tag{6d}$$

in which the value of constant λ is found to be 343.79, 252.03, and 171.91 for intermittent flame height, mean flame height, and continuous flame height, respectively.

However, when the fire is momentum controlled, the flame height will not increase with fuel supply rate anymore. The flame height of an asymmetrical source is only dominated by the characteristic length, that is, source diameter. Meanwhile, in the case of a linear source, the characteristic length should be the hydraulic diameter (or the surface area divided by the perimeter of the source).

Axial temperature profiles

Usually, for the temperature profile of a fire plume, overall three regions are clarified as the continuous flame region where the presence probability is 0.95 from the flame base, the intermittent flame region where the presence probability is 0.95 down to 0.05, and the upper buoyant plume region from the presence probability 0.05 according to Audouin et al.'s[24] proposal. So, it is easy to determine these three regions based on the results in section "Flame heights": continuous flame region ($Z<0.0144\dot{Q}_l'^{2/3}$), intermittent flame region ($0.0144\dot{Q}_l'^{2/3}<Z<0.0287\dot{Q}_l'^{2/3}$), and buoyant plume region ($Z>0.0287\dot{Q}_l'^{2/3}$).

Figure 5 plots the normalized temperature rise against the normalized height above the line fire source. We can make the following observations regarding four different regions for a line-source jet fire plume:

1. There is a small temperature rising phase in the continuous flame region when $Z<0.004\dot{Q}_l'^{2/3}$, and the temperature remains a constant in continuous flame region when $0.004\dot{Q}_l'^{2/3}<Z<0.014\dot{Q}_l'^{2/3}$.
2. The temperature rise in the intermittent flame region follows a -1.8 power of normalized height before it falls into the -1 power for the line-plume region.

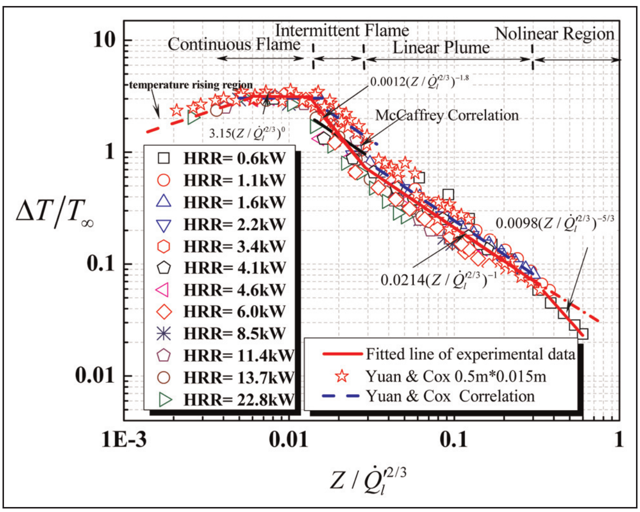

Figure 5. Normalized axial temperature profile behaviors in four transition regions.
HRR: heat release rate.

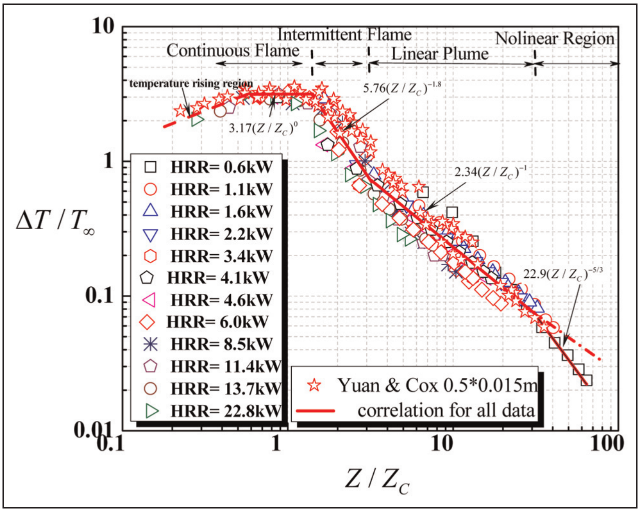

Figure 6. A proposed global non-dimensional four-regions correlation for axial temperature profile.
HRR: heat release rate.

3. The temperature rise decay profile in the buoyant plume region breaks from the −1 power behavior to a steeper gradient of −5/3 at height $Z \approx 0.3\dot{Q}_l'^{2/3}$ (before which can be deemed as line-plume region meanwhile after which can be deemed as axi-symmetrical-plume region). This is because the plume will eventually grow to be a three-dimensional (3D) one at an enough distance above the line-source nozzle.

Finally, we would like to propose a global non-dimensional correlation formula for the axial temperature profile in these four regions (continuous flame region, intermittent flame region, line-plume region, and axi-symmetrical-plume region) for a line-source jet fire based on the above discussion

$$\frac{\Delta T}{T_\infty} = \kappa \left(\frac{Z}{Z_C} \right)^{\eta} \tag{7a}$$

as exemplified in Figure 6, where Zc is the characteristic length scale of the line fire source defined as

$$Z_C = \left(\frac{\dot{Q}'_l}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/3} \tag{7b}$$

The correlated values for constants (κ, η) in equation (7a) are summarized in Table 1 for the four different regions. However, it is also noted that correlation of temperature profile based on mixture fraction,[25] especially for that below flame height, will be a valuable potential work to find out how it evolves, or transits between these different regimes. It is also more useful to distinguish these transits more directly by high resolution 2D temperature measurement through some non-interference method in the future.

Table 1. Correlated values of constants for axial temperature profiles in four regions (equation (7)).

Temperature region	Profile range	κ	η
Continuous flame	$Z/Zc < 1.39$	3.17	0
Intermittent flame	$1.39 < Z/Zc < 3.07$	5,52	−1.8
Line-plume	$3.07 < Z/Zc < 32.2$	2.25	−1
Axi-symmetric-plume	$Z/Zc > 32.2$	22.8	−5/3

Conclusion

This article investigates experimentally flame height and axial temperature profile of a buoyant turbulent line-source jet fire plume, with non-dimensional global correlations, which are newly proposed. Major findings include

1. The flame heights can be well correlated non-dimensionally by the flame Froude number $\ell_f/((S+1)^{2/3}W(\rho_s/\rho_\infty)^{5/6}) = \lambda Fr_f^{2/3}$. The values of λ for continuous flame height, mean flame height, and intermittent flame height are found to be 171.91, 252.03, and 343.79, respectively.
2. A global non-dimensional four-regions correlation (continuous flame region, intermittent flame region, line-plume region, and axi-symmetric-plume region) is proposed to well correlate the axial temperature profile induced by a line-source jet fire. The temperature profile in the intermittent flame region is found to follow a −1.8 power of Z/Z_C. The temperature profile transforms into a nearly axi-symmetric one at a critical height of about $Z/Z_C \approx 32.2$. The formula constants for axial temperature profiles in the four different regions are suggested (Table 1).

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Appendix I

Notation

C_P	specific heat of air at constant pressure (kJ/(kg K))
Fr_f	flame Froude number
g	gravitational acceleration (kg m/s^2)
L	length of linear burner (m)
ℓ_f	flame height (m)
ℓ_p	length scale for line-source
$\dot{Q}$	heat release rate of the fire source (kW)
$\dot{Q}'_l$	heat release rate of fire source per unit length (kW/m)
R_l	mass burning rate per unit length
T_∞	ambient air temperature (K)
ΔT	centerline temperature rise (K)
$\overline{\Delta T_f}$	mean peak flame temperature rise (K)
W	width of the linear burner (m)
Zc	characteristic length scale of line-source (m)

Greek symbols

Δ	difference between variables
κ,η	constants in temperature profile correlation
λ	constant in flame height correlation
ρ_∞	ambient air density (kg/m^3)
ρ_s	fuel density at nozzle (kg/m^3)

Subscript

$f\text{–}c$	continuous flame
$f\text{–}m$	mean flame
$f\text{–}i$	intermittent flame
l	linear fire source
s	gas fuel
∞	ambient

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