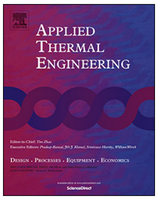
Applied Thermal Engineering 93 (2016) 884–887

Contents lists available at ScienceDirect

Applied Thermal Engineering

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



Experimental determination of flame length of buoyancy-controlled turbulent jet diffusion flames from inclined nozzles

Changfa Tao, Yan Shen, Ruowen Zong *

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China

HIGHLIGHTS

- Flame length addressing the effect of inclined angle for the jet flames.
- The entrainment constant parameter C_1 is generally proportional to $\cos\theta_0$ linearly.
- A global model is proposed for flame length of jet flames from inclined nozzles.

ARTICLE INFO

Article history:
Received 25 June 2015
Accepted 16 September 2015
Available online 3 December 2015

Keywords:
Inclined nozzles
Flame length
Heat release rate
Jet flames

ABSTRACT

Flame length of buoyancy-controlled turbulent jet diffusion flames from inclined nozzles with inclined angles of 0°, 30°, 45°, 60°, and 90° to the horizontal has been investigated experimentally in this work. The jet diffusion flames are produced by the nozzles with diameters of 8, 12, and 16 mm. The relationship between flame length and heat release rate has been proposed for jet flames from inclined nozzles. It is found that the values of the entrainment coefficient C_1 are generally proportional to $\cos\theta_0$ linearly. A global model when Froude number is below about 300 ($Fr < 300$) is developed for estimating the flame length of the buoyancy-controlled jet flames from inclined nozzles.

1. Introduction

Extensive studies have been conducted for vertical [1–5] and horizontal jet flames [6]. The semi-empirical model of flame height was developed based on heat release rate [2–4] or Froude number [7–9]. The theoretical analysis about turbulent jet flow from a nozzle into still air with an angle θ_0 to the horizontal has been finished [7]. The inclined angle of the flame central line at different locations can be described by the following equation [8,9]:

$$\tan\theta = \tan\theta_0 + \frac{1}{\sqrt{\rho_0/\rho_\infty}\cos\theta_0 Fr^*}\left[\left(\frac{s}{D}\right) + 2\beta\left(\frac{s}{D}\right)^2 + \frac{4}{3}\beta^2\left(\frac{s}{D}\right)^3\right] \qquad (1)$$

where the modified Froude number is $Fr^* = \frac{u_0^2}{gD}\sqrt{\rho_0/\rho_\infty}\frac{\rho_\infty}{(\rho_\infty - \rho_{st})}$, $\beta = \frac{b(s)}{s} = \frac{16}{\mathrm{Re}}\sqrt{\rho_0/\rho_\infty}$, and $\mathrm{Re} = \frac{u_0 D}{\nu}$, θ_0 is inclined angle of the nozzle, u_0 is the initial velocity of gas fuel from the nozzle. This model has been verified by the experiments of non-reacting buoyant jets and buoyant jet flames [9]. The model of flame height was developed based on the dimensionless heat release rate, which could be used to estimate the entrainment coefficient [2].

However, the jet flames from inclined nozzles often happened as the leakage of combustible gas occurred. The evolution of flame length with the increase of inclined angle, from 0° to 90° to the horizontal, needs to take more attention. The impact of inclined angles on entrainment rate of jet flames also needs to be clarified and quantified.

In this paper, a series of experiments have been conducted. A global relation has been developed to characterize the transitional behavior of jet flame length for the angles of 0°, 30°, 45°, 60°, and 90° to the horizontal.

2. Experimental section

In this paper, the inner diameters of the circular nozzles are designed for 8, 12 and 16 mm, and the different slope angles of 0°, 30°, 45°, 60°, and 90° to the horizontal are considered. For each nozzle, 4~5 cases with different fuel mass flow rates are studied, and each case is repeated for 2~3 times, as described in Table 1. LPG

---

* Corresponding author. Tel.: +86 551 63606439; fax: +86 551 63601669.
E-mail address: zongrw@ustc.edu.cn (R.W. Zong).

http://dx.doi.org/10.1016/j.applthermaleng.2015.09.049
1359-4311/

Table 1
Summary of experimental scenarios.

Inclined angle	Diameter		
	D = 8 mm	D = 12 mm	D = 16 mm
	Volume flow rate (m^3/h)	Volume flow rate (m^3/h)	Volume flow rate (m^3/h)
0°	0.074/0.148/0.296/0.445/0.74	0.074/0.148/0.296/0.445/0.74	0.074/0.148/0.445/0.74
30°	0.074/0.148/0.296/0.445/0.74	0.074/0.148/0.296/0.445/0.592	0.148/0.296/0.445/0.74
45°	0.265/0.397/0.53/0.662/0.795	0.265/0.397/0.53/0.662/0.795	–
60°	0.074/0.148/0.296/0.445/0.74	0.074/0.148/0.296/0.445	0.074/0.148/0.296/0.445/0.74
90°	0.074/0.148/0.296/0.445	0.074/0.148/0.296/0.445	0.074/0.148/0.296/0.445

(Liquefied Petroleum Gas) is the fuel used to provide a steady fuel supply controlled by a flow meter. The flame length is recorded by a digital Charge-Coupled Device (CCD) camera of 60 frames per second at a distance of 1.5 m away for at least 120 seconds. The ambient conditions: the temperature is 25 ± 2 °C, the pressure is 101 ± 5 kPa, and the humidity is 20 ± 10%.

As described in Fig. 1a, the method to obtain the flame length is described as follows: First, the locations of nozzles in figures are confirmed. Then, in order to determine the flame trajectories from the nozzle to the flame peak, four central points are chosen at different locations by measuring the horizontal width where the presence probability is 0.5 [1]. The lowest and the highest points are confirmed at the central point of nozzles and the peak point of flame, respectively. Finally, the flame length can be obtained based on Eq. (1).

3. Experimental results and discussion

The dimensionless flame length of jet flames (L_f/D) can be plotted against $Fr^{0.2}$ ($Fr = u^2/gD$) by functions for each inclined angle. Here, the best fit for our experimental data is found to be in close proximity to that proposed by Peter and Gottgens [7] shown in Fig. 1b. In fact, most of their experimental results about jet flames are finished at $Fr > 300$ and only two points exit at $Fr < 300$, hence it is difficult to find the differences of jet flames with different inclined angles [7]. In order to study the flame length of buoyancy-controlled turbulent jet diffusion flames under low Froude number, many experiments were finished at $Fr < 300$ in this work.

The theoretical analysis is based on the following hypothesis, which is generally adopted in the fire plume theories [2,3]. For the fires, it gives:

$$Q_s^* = 0.0059\frac{\psi^{3/2}}{1-\chi_r}\left(\frac{L_f}{D}\right)^{\frac{1}{2}}\left[1+2C_1\left(\frac{L_f}{D}\right)\right]^2 \tag{2}$$

where the dimensionless heat release rate $Q_s^* = Q\Big/\left(\rho_\infty T_\infty C_p\sqrt{gD^5}\right)$; ψ could be calculated as:

$$\psi = \frac{(1-\chi_r)(\Delta H/s')}{C_p T_\infty} \tag{3}$$

where $\chi_r = 0.2$, $C_1 = (6/5)\alpha$, $\Delta H_c/s' = 2.9$ kJ/g [2]. Q_s^* against L_f/D under different inclined angles θ_0 can be plotted. For the vertical axisymmetric sources, the value of the entrainment coefficient C_1 (0.184) is close to those proposed by Quintiere and Grove [2] (0.1785) and Hu et al. [3] (0.185). The fitting results for jet flames from different inclined angles θ_0 are shown in Fig. 2a. It can be found that the relationship between C_1 and θ_0 can be well described globally by Eq. (4), which indicates that the entrainment coefficient decreases with θ_0. Their relationship can be described as:

$$C_1 = 0.183 + 0.142 \cdot \cos\theta_0 \tag{4}$$

As shown in Fig. 2, the visible flame length is quantified against dimensionless heat release rates (in this paper, $Q_s^* < 3000$, shown in Fig. 2a and Fig. 3a and c). The flame length cannot be calculated

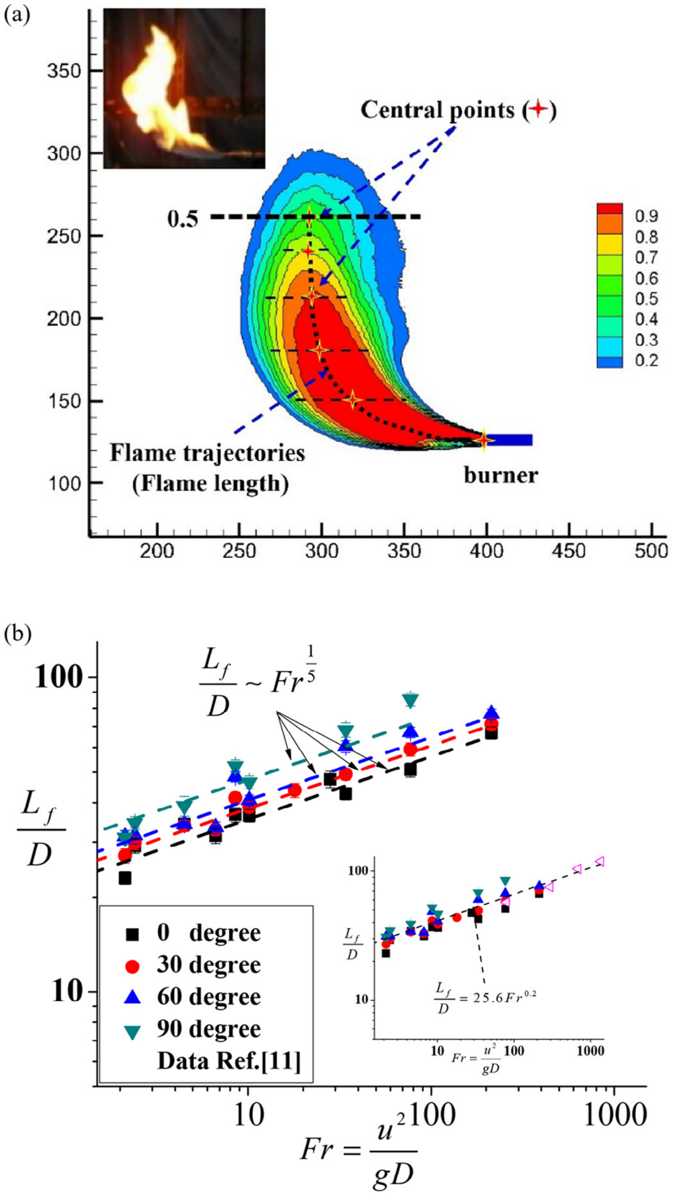


Fig. 1. The acquisitive method for flame length and confirmation. (a) Mean flame length at 0 degree (e.g. D = 8 mm, 0.445 m³/h). (b) The relationship between L_f/D and Fr.