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Full Length Article

Effect of crossflow on the air entrainment of propane jet diffusion flames and a modified Froude number

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ABSTRACT

Gas leakage fire is increasingly common with urbanization and industrialization. Understanding of the entrainment behavior of the jet flame is significant to improve the fuel security management and fire prevention strategy. Many studies have been done in still air and limited studies have focused on the air entrainment of the jet flame under crossflow. This work firstly deduced an expression of the air entrainment ratio (n) incorporating with the flame length and tilt angle based on the momentum balance and, defined a modified Froude number (Fr^*) to explore effects of the inertia force (owing to the fuel jet and crossflow) and the combustion-induced buoyancy. Secondly, experiments of propane jet diffusion flames under crossflow were performed. Fuel jet Reynolds number (Re) and jet-to-crossflow momentum flux ratio (R_M) were 310–3305 and 0.004–124, respectively. The flame length divided by Re first increased and then decreased with R_M, and its curves were more like parabolas other than polylines. The flame tilt angle decreased with R_M. Moreover, Fr^* had a negative relationship with R_M, indicating the jet and crossflow momenta, instead of combustion-induced buoyancy, gradually dominated the air entrainment with increasing wind velocity. The calculated n was dominated by the flame length but effected by the tilt angle, because the local entrainment velocity was proportional to the magnitudes of the crossflow velocity and flame axial velocity differences that were relevant to the flame tilt angle. Finally, there were three trends of n with Fr^* according to Re. For $Re < 900$, the crossflow was always dominant and n varied slowly. For $900 < Re < 2300$, n first grew quickly with stretched and slightly inclined flames and then decreased to some almost constants with nearly horizontal flames. For $Re > 2300$, n increased rapidly owing to the dominated-effect of the momentum and then decreased until the flame began to shorten.

1. Introduction

Gas leakage fire, for example liquefied petroleum gas (LPG) fire, is more and more common with urbanization and industrialization. For numerous gas transport pipelines in chemical processing plants, once the gas leakage fire occurs, it is very easy to cause a three-dimensional fire resulting in enormous economic losses. It is significant to study the behavior of the jet propane flame in order to improve the fuel security management and fire prevention strategy.

The reactive jet or jet flame is a classical, continuous project in the fields of combustion and energy security [1]. Among amounts of parameters describing the flame behavior, the air entrainment rate is directly related to the flame size and smoke production [2–6].

In the quiescent condition, a classical entrainment hypothesis for the plume is that the horizontal entrainment velocity u_h is proportional to the gas upward velocity u_g, i.e. [7,8],

$$u_h = \alpha u_g, \tag{1}$$

where α denotes the entrainment coefficient. And many studies under varied boundary conditions have been conducted based on this hypothesis, such as sidewalls [4], coflow [9], sub-atmospheric pressure [3], double jet flames [6], and multiphase flow [10].

Another air entrainment theory is about the axial mass flow rate or the flame width by Ricou and Spalding [11] as follows:

$$\frac{\dot{m}(z)}{\dot{m}_j} = 0.32\frac{z}{d_j}\left(\frac{\rho_f}{\rho_j}\right)^{1/2}, \tag{2}$$

where $\dot{m}(z)$ is the mass flow rate across the section perpendicular to the flame axis at the height z, $\dot{m}_j$ is the mass flow rate of the jet, d_j is the nozzle diameter, ρ is the density, and the subscripts f and j denote the flame and the fuel jet, respectively. It is also widely used to predicate the flame behavior under crossflow, such as Refs. [12–15].

What's more, the entrainment number at the flame tip, which is

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Nomenclature

A_f	sectional area
d_j	diameter
Fr	Froude number
Fr^*	modified Froude number
g	gravitational acceleration
H	height
k	appearance parameter
l_f	flame length
$\hat{L}_f$	effective dimensionless flame length, Eq. (12)
L_f	dimensionless flame length, l_f/d_j
$\dot{m}$	mass flow rate
M_{Air}, M_{N_2}	molecule weight of air or N_2
n	entrainment ratio
Re	Reynolds number
Ri	Richardson number
R_M	jet-to-crossflow momentum flux ratio
S	stoichiometric air-fuel mass ratio
T	temperature
u	velocity
w_f	flame width
x, y, z	Cartesian coordinates

Greeks

α	entrainment coefficient in Eq. (1)
$\alpha_{e(u)}$,$\beta_{e(u)}$	entrainment coefficients in Eq. (3)
β	entrainment coefficient in Eq. (8)
θ	flame tilt angle
μ	dynamic viscosity
ξ	axial coordinate of the flame
ρ	density

Subscript

b	buoyancy
f	flame
g	gas
h	horizontal direction
j	jet
w	wind
∞	ambient condition

defined as the ratio of the entrained air up to the flame tip with the stoichiometric air required, is an important measurement parameter at about 5–20 [16–19]. Besides, Cetegen [20] developed a phenomenological model of near-field air entrainment into combusting regions of axisymmetric fire plumes based on periodic engulfment of ambient air by toroidal vortices present.

Under crossflow, the entrainment rate is commonly assumed proportional to the magnitudes of the velocity along the flame inclined axis $u(\xi)$ and the wind velocity u_w differences [21,22], and Escudier [21] wrote it as follows:

$$d\dot{m}(\xi)/d\xi = \pi\rho_\infty w_f[\alpha_{e(u)}|u(\xi){-}u_w\sin\theta| + \beta_{e(u)}u_w\cos\theta], \tag{3}$$

where $\dot{m}(\xi)$ is the mass flow rate across the section normal to the flame inclined axis at axis coordinate ξ; w_f is the flame width; u is the velocity, θ is the flame tilt angle inclined from the nozzle axis; $\alpha_{e(u)}$ and $\beta_{e(u)}$ are the air entrainment coefficients related to the components of the crossflow velocity parallel and normal to the flame axis and the values of them are suggested to be 0.057 and 0.5, respectively; and the subscript ∞ denotes the ambient condition.

Tao et al. [23] studied the entrainment coefficients of buoyancy-controlled turbulent jet diffusion flames produced by inclined burners with various inclined angles, and the entrainment coefficient had a generally linear relationship with the tangent value of the inclined angle. Tsue et al. [2] found that the mixing of fuel and air, as well as the chemical reaction proceeds, was enhanced by the counter-rotating vortices pairs (CVP). Besides, the results of temperature and velocity indicated that the cross-flow air was entrained into the upper edge of the flame by coherent structures with large vortices.

The previous literatures have focused either on the flames in still air, or on the deduced implicit solutions of flame entrainment rate in crossflow, and limited works have studied the air entrainment of the jet flame under crossflow condition. In this study, an explicit relation between the flame entrainment, and the flame length and tilt angle was deduced based on the momentum balance. Furthermore, a modified Froude number was defined in order to examine the effects of the momentum induced by jet and crossflow, and the combustion-induced buoyancy. Finally, the calculated air entrainment ratio was analyzed and had three different trends with the modified Froude number based on jet Reynolds number.

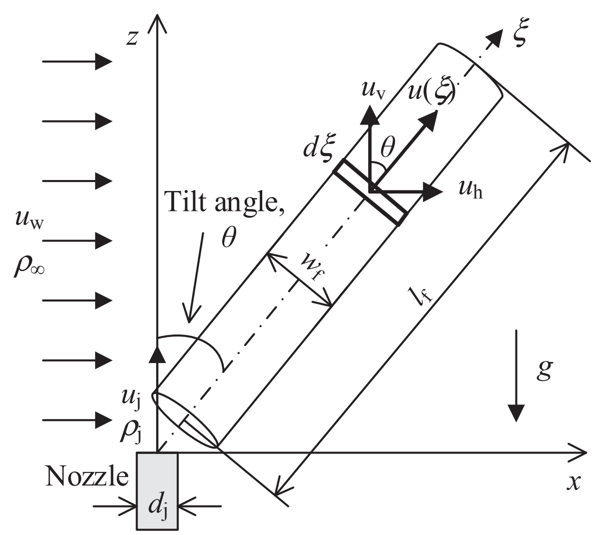

Fig. 1. Sketch of the flame under crossflow, and definitions of flame length l_f, flame width w_f, gravitational acceleration g, coordinates at horizontal, vertical and flame axial directions x, z and ξ, horizontal and vertical velocity components u_h and u_v, gas velocity along the flame axis $u(\xi)$.

2. Theoretical method

For a jet flame in low speed cross wind condition as shown in Fig. 1, there are some assumptions: (a) the flame has a cylindrical shape, and the flame width is proportional to the flame length as $w_f = kl_f$, where k is an appearance parameter [15,24,25]; (b) the homogenous, isothermal flame is adopted; (c) the velocity of the hot gas initially equals the jet velocity at the nozzle exit and increases at an acceleration generated by the combustion-induced buoyancy, meanwhile the direction of the velocity is changed by the crossflow. Besides, the gas velocity is distributed evenly in the section normal to the flame axis.

The mass flow rate of a diffusion flame at a certain coordinate ξ can be expressed as follows [8]:

$$\dot{m}(\xi) = \frac{1}{4}\pi\rho_f u(\xi)w_f(\xi)^2. \tag{4}$$

The velocity along the flame axis $u(\xi)$ is determined by the balance