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Flame downwash transition and its maximum length with increasing fuel supply of non-premixed jet in cross flow

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ABSTRACT

The present study experimentally investigated the flame downwash transition and its maximum length that can be reached at leeward side of nozzle with increasing fuel supply of non-premixed jet in cross flows. Experiments were conducted with 8, 10, 13 and 15 mm nozzles, using propane and methane as fuel. The cross flow speed ranges from 0.70 to 3.08 m/s while the fuel jet velocity ranges between 0.04 and 4.26 m/s. Results showed that, with increasing fuel supply at a given cross flow speed, flame downwash length first increased (fuel supply controlled regime) then decreased (leeward side reversing flow rotating strength controlled regime). A function between the jet-to-crossflow momentum flux ratio (R_c) and dimensionless fuel mass flow rate ($\dot{m}_c^*$) was proposed to illuminate the tuning state of above transition. The flame downwash maximum length at the turning state normalized by nozzle diameter was found to have a linear relation with Froude number of fuel jet ($Fr_j = u_j/\sqrt{gD}$) or cross flow ($Fr_a = u_a^2/gD$). These findings contribute to a better understanding of flame downwash evolution process, which could have a basic significance for reducing fuel emission, improving combustion energy efficiency and saving energy by controlling the flame downwash scale.

1. Introduction

A non-premixed jet flame in cross flow is a common scenario, which could be formed due to burning of accidental gas leakage of city gas fuel pipeline, as well as in industrial combustion system (e.g., flaring). Flame downwash phenomenon is observed as fuel being trapped into the wake region of the nozzle, combusting and producing a flame attached to the leeward side. It is of greatly significance for not only fire protection and the burner design, but also energy conversion and conservation [1–6]. The flame downwash will change essentially the heat impact to the burner and lead to the damage to the burner (i.e., flare system). Therefore, the flame downwash length in cross flows is basically an essential parameter for gas burner design and fire protection (i.e., the range below the top of the burner where heat-resistant material should be specially installed for fire protection).

The combustion characteristics of non-premixed jets in crossflow have been extensively investigated due to its significance to burner design and energy conservation [7–24]. However, the studies on the flame downwash behavior are still very limited [1,25,26]. In early years, Gollahalli and Nanjundappa [1] used a burner (5.0 mm i.d. and 6.4 mm o.d.) with propane as fuel, identified the flame downwash phenomenon in their experiments. Huang and coworkers [24], employing the burner of same dimensions [1], confirmed that the downwash and reversing flow regions lie in the leeward side of the burner acted as the primary mechanism related to the flame stabilization.

Till now, only two quantitative studies on the flame downwash length are available in the literature [25,26]. Majeski [25] first quantified the flame downwash length experimentally for a single nozzle (22.1 mm in diameter) and a fixed propane mass flow supply rate (jet velocity is 1.0 m/s), and speed of cross flow ranged from 2 to 10 m/s. A formula was proposed for the flame downwash length (L_d),

$$\frac{L_d}{D} = 13.6\ln\left(\frac{1}{R^{1/2}}\right) - 1.29\ (0.014 \le R \le 1.3) \qquad (1)$$

where D represents the pipe diameter, and R represents the jet-to-crossflow momentum flux ratio given by:

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Nomenclature

D	nozzle inner diameter [mm or m]
g	gravitational acceleration [m/s^2]
L_d	flame downwash length [cm or m]
$\dot{m}$	fuel mass flow rate [kg/s]
$\dot{m}^*$	dimensionless fuel mass flow rate
R	jet-to-crossflow momentum flux ratio
u_a	cross-flow air speed [m/s]
Fr_j	Froude number of fuel jet
Fr_a	Froude number of cross flow
$u_{a,mean}$	mean of the cross-flow air speed [m/s]
$u_{a,rms}$	root mean square of the cross-flow air speed [m/s]
$\dot{m}_c^*$	critical dimensionless fuel mass flow rate when flame downwash length reaches its maximum value
R_0	critical jet-to-crossflow momentum flux ratio when the flame downwash occurs
R_c	critical jet-to-crossflow momentum flux ratio when flame downwash length reaches its maximum value
$u_{j,c}$	critical fuel jet when flame downwash length reaches its maximum value [m/s]

Greek symbols

ρ_a	ambient air density [kg/m^3]
ρ_j	fuel density at exit [kg/m^3]

Subscripts

a	cross-flow of air
j	fuel
mean	statistical mean value
rms	statistical root mean square value

$$R = \frac{\rho_j u_j^2}{\rho_a u_a^2} \quad (2)$$

in which u_j and u_a is the velocity of fuel jet and the speed of cross flow respectively; likewise , ρ_j and ρ_a is the density of fuel and ambient air, respectively.

Later recently in 2017, Shang [26] quantified the flame downwash length for four different nozzle diameters. As well as Majeski, only propane was used as fuel. The flame downwash lengths were measured for several fixed fuel jet velocities, while speed of cross flow was increased and the range of jet-to-crossflow momentum flux ratio was between 0.0078 and 4.87. A more general non-dimensional formula was correlated, based on the newly proposed physics (Fig. 9 in Ref. [26]) suggesting that the flame downwash length be determined jointly by the amount of propane supply (or the total characteristic length of the flame) and the jet-to-crossflow momentum flux ratio (its reciprocal ($1/R$) describes the reversing flow rotating strength at the leeward side, hence the portion of the fuel that can be dragged into the recirculation wake region of the nozzle to form the downwash), which gives

$$\frac{L_d}{D} = 2.095\dot{m}^{*3/2}\left(\frac{1}{R^{1/2}} - \frac{1.41}{m^{*1/2}}\right)\ (0.0078 \le R \le 4.87) \quad (3)$$

where a non-dimensionless fuel mass flow rate ($\dot{m}^*$) was found to be another essential parameter, in addition to jet-to-crossflow momentum flux ratio (R), which can be given by:

$$\dot{m}^* = \frac{\dot{m}}{\rho_a g^{1/2} D^{5/2}} \quad (4)$$

in which $\dot{m} = \rho_j u_j \pi \left(\frac{D}{2}\right)^2$ represents fuel mass flow rate and g is the gravitational acceleration constant. Besides, the critical air speed of cross flow beyond which the flame being trapped into the recirculation vortex that the flame downwash phenomenon can be observed to occur was also quantified [26] for various nozzle diameters and fuel jet velocities, which showed to be well represented by the following general formula,

$$R_0 = 0.503\dot{m}^* \quad (5)$$

where R_0 is the critical momentum flux ratio for flame downwash occurrence at the leeward side.

However, there could be another kind of transition and associated critical limit of the flame downwash length evolution that need to be quantified essentially. That is, with a given cross flow speed, how the flame downwash length evolves as the fuel jet velocity increases. One can imagine that as the fuel jet velocity is zero (no fuel) or at very high enough value (flame lift off), the corresponding flame downwash length should be both zero accordingly. This is due to naturally that (indicated by Eq. (3)) as the fuel jet velocity increases, both the fuel mass supply rate ($\dot{m}^*$) and the jet-to-crossflow momentum flux ratio (R) increase. So with a cross flow, the downwash length of non-premixed wake-stabilized flame must first increase then decrease with increasing of fuel jet velocity, and a maximum value of flame downwash length will result in as the above two mechanisms reach a kind of balance. The flame downwash maximum length could be the most crucial parameter for the burner protection design. This kind of transition and associated maximum length of the flame downwash have not been quantified yet, however, being essentially basic knowledge for this topic.

In the present study, the flame downwash transition with increasing fuel supply of non-premixed jet was quantified for both propane and methane, under various cross flow air speeds and nozzle diameters. The flame downwash maximum length that can be reached, as well as its corresponding critical turning state of the transition were revealed, and represented by proposed non-dimensional formulas. The findings obtained provides a basic knowledge for the calculation of the maximum flame downwash length, which could have a promising application in industrial burner design and gas disposal flare installation. It also offers a new method to reduce fuel emission, improve combustion efficiency and save energy by controlling the flame downwash scale, which is of much significance for atmosphere protection, energy utilization and conservation.

2. Experiments

The experimental setup is depicted in Fig. 1. The cross flow was produced by a mechanical fan installed at one end of the tunnel, then going through a honey-comb installed close to the fan, with turbulence fluctuation, $u_{a,rms}/u_{a,mean}$, being less than 5% in the experimental section. The speed of cross flow was monitored by a hot-wire anemometer placed 0.5 m ahead of the nozzle whose accuracy is 0.01 m/s. More details about the wind tunnel can be found in Ref. [26].

Non-premixed jet flames were produced from the exit of four different sizes stainless circular pipe nozzles. Commercial propane