Stabilization Mechanism of Burner-attached Flames in Laminar Non-premixed Jets

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ABSTRACT
The stabilization mechanism of nozzle-attached flames in laminar non-premixed jets was studied experimentally and numerically. The local gas flow velocity and the flame propagation speed within the mixing layer at flame base were experimentally obtained before the blowout limit was reached. The experimental results show that, for burner-attached flames, the local flow velocity is much less than the burning speed, suggesting that the propagation of partially premixed flame within the mixing layer at flame base is stopped. The thickness of the fuel/air mixing layer at the attached flame base is quite narrow (1.1–1.5 mm) and less than the minimum quenching distance caused by conductive heat loss to the tube (or slit) wall in laminar premixed flame. Heat losses by the conduction from the flame base to the burner wall, and the convection between the flame base and the incoming flow (hereafter referred to as local convection) were studied through simulation. The significant roles of these effects in the stabilization of the attached flame were analyzed. While the heat loss by conduction to the fuel tube is neglected, the partially premixed flame at flame base can propagate along a much narrower mixing layer. On the contrary, a critical thickness of the mixing layer (in which the local partially premixed flame can sustain) exists near the flame base with considering the conductive heat loss. The conductive heat loss to the burner wall plays a relatively important role to flame stabilization without (or with a small amount of) coflow air. As the velocity of coflow air increases, the heat loss due to local convection gradually exhibits significant effects on flame stabilization. In addition, a simple theoretical model is provided based on the balance between the heat released by chemical reaction and the heat lost by conduction and local convection, suggesting clear dependence of the thickness of the fuel/air mixing layer on the local gas flow velocity and the laminar flame speed. The stability behaviors of flame base can be reasonably explained and predicted through such relation.

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Introduction
Burner stabilized laminar diffusion flames are found when the velocity of a fuel jet or the surrounding air co-flow velocity is below certain critical values. The flame can remain...
attached near the burner exit over a range of jet velocity until the critical velocity is reached and the flame is lifted considerably away from the burner or blows off entirely. Fundamentally, attached laminar jet flames are of interest because they exhibit representative characteristics of diffusion flames such as fuel/oxidizer mixing, flow-chemistry interaction, and effects of heat release. This rather simple configuration also greatly facilitates experimental and theoretical investigations which are relevant to more complicated turbulent diffusion flames.

For the laminar attached diffusion flames, although the vertical clearance is quite small (0.1–0.7 nozzle rim thickness (Ikeda and Beduneau 2005; Juniper and Candel 2003; Lamige et al. 2014; Otakeyama, Yokomori, Mizomoto 2009; Robson and Wilson 1969)), and the flame base is often located at or below the nozzle exit at low jet velocity conditions (Kawamura, Asato, Mazaki 1980; Takahashi et al. 1985), a small volume of partial premixed fuel/air gases can still exists at the flame base (Ikeda and Beduneau 2005; Juniper and Candel 2003; Kawamura, Asato, Mazaki 1980; Lamige et al. 2014; Otakeyama, Yokomori, Mizomoto 2009; Peters 1984; Robson and Wilson 1969; Takahashi et al. 1985). It has been generally speculated that flame lifting is inhibited due to the presence of downward propagation speed near the partially premixed zone at the flame base. The base of flame hence stabilizes at a position where the maximum laminar burning velocity of gas mixture is balanced with the local jet velocity (Kawamura, Asato, Mazaki 1980; Peters 1984), which is similar to the stabilization mechanism of laminar lifted diffusion flames (Chung and Lee 1991; Kim, Won, Chung 2007). In a typical free jet configuration, the fuel-stream jet is forced vertically upward into ambient air (oxidizer), and then mixing between fuel and oxidizer streams occurs due to macroscopic fluid motion and molecular diffusion. A mixing layer gradually grows as the axial distance from nozzle exit increases. While an appropriate ignition energy is introduced further downstream of such flow structure, a flame front is expected to form and propagate through this fuel/oxidizer mixing layer until it arrives at the stabilization position. In a coflow jet configuration, the presence of coflow air can promote or weaken the mixing between fuel and air streams depending on the velocity difference. Ko and Chung (1999) and Lee et al. (2003b) investigated the propagation of triple flames in laminar diffusion jets and obtained the propagation speeds by igniting jets at a farther downstream location of the nozzle. Some numerical results (Takahashi and Katta 2000a, 2000b; Takahashi, Schmoll, Katta 1998) showed that the thickness of the methane/air mixing layer within 0.6–0.8 mm near the attached flame base is less than the minimum quenching distance (2.2 mm). Takahashi and Katta (2000a, 2000b) claimed that an ordinary premixed flame cannot form within this extremely narrow mixing layer, thus suggesting that the triple flame theory or the premixed flame concept is inapplicable. The peak reactivity spot at flame base, i.e. a reaction kernel (Takahashi and Katta 2000a, 2000b, 2005), was shown to exhibit different structure than in triple flames or the ordinary premixed flames. Such observation indicates the significance of mixing process of fuel/air streams to the stabilization of a laminar attached diffusion flame. Nonetheless, further investigation is still needed to resolve contradictions and limitations in understanding the flame stabilization mechanism.

It is known that a lifted flame is thermally dissociated from the upstream burner wall. An attached flame, on the contrary, allows inevitable heat transfer between the flame base and the burner rim such that it has critical effects on the flame stability (Gao et al., 2017). As heat losses to the nozzle rim can also create ‘dead space’ (or dark space) in a diffusion flame near
the nozzle exit (Peters 1984; Takahashi, Schmoll, Katta 1998), effect of convection between the flame base and the incoming flow (local convection) on maximum temperature of flame base can be rather considerable (Robson and Wilson 1969). Experimental results of Lamige et al. (2014) showed that nozzle coating exerts minimal influence on the lip temperature and the flame stability. Some previous numerical investigations simply neglected the radiative heat transfer from the flame base (Gao et al., 2017; Takahashi, Schmoll, Katta 1998; Xiong, Cha, Chung 2015). Therefore, it could be plausibly concluded that the upstream conduction and local convection mainly dominate the heat losses near the attached flame base. However, Robson and Wilson (1969) and Kawamura, Asato, and Mazaki (1980) have shown that a larger portion of heat released by the flame base is transferred to the fuel jet instead of to the burner wall or coflow air. Lamige et al. (2014) found that the burner lip temperature of an attached flame decreases linearly with jet velocity from 440 K at jet exit velocity of 1.3 m/s down to 345 K at near lifting condition (14.9 m/s) owing to the convection between the burner wall and the fuel flow (hereafter referred to as burner convection) (Robson and Wilson 1969). Interaction between the local gas flow and the burner wall can further complicate the stabilization mechanism of laminar attached diffusion flame. Furthermore, there is little quantitative data on the relative weight of effects of heat losses by conduction and local convection on the attached flame stability. Demands to further comprehend the effects of heat losses by conduction and local convection on the flame stabilization motivated our study.

In this work, we aim at investigating the stabilization mechanism of a laminar nozzle-attached jet diffusion flame. Both the attached and the lifted flames were obtained experimentally, and the location of flame base can be adjusted by variation of fuel jet velocity, fuel dilution level and coflow air velocity. The local gas flow velocities at flame base were measured by PIV. By igniting jets at a location farther downstream of the nozzle, propagating flames were created and their speeds within the fuel/air mixing layer at flame base were obtained from consecutive high-speed images. The burner-attached flame stabilization mechanism was then examined by comparing the local flow velocity with the burning speed. Results from numerical simulations were used to assist analyzing the influences of heat losses by conduction to the burner wall and local convection on the stabilization of burner-attached diffusion flames. Moreover, heat losses by conduction and local convection are quantitatively analyzed and used to explain their important roles in the stabilization of a laminar attached diffusion flame.

**Experiment and numerical simulation**

**Experiments**

The experimental setup is illustrated in Figure 1. It is mainly composed of a coflow burner, a gas supply system and a measurement system. The cylindrical coflow burner is made of stainless steel with a central fuel nozzle with inner diameter of 3.175 mm, lip thickness of 0.5 mm. The fuel nozzle is surrounded by a coflow air nozzle with an inner diameter of 50 mm. The coflow air passes through glass beads and honeycomb material to retain flow uniformity at the exit. The fuel is grade methane (>99.5%) diluted with nitrogen (>99.99%). Methane and diluent gases were premixed before entering the burner. Mass flow controllers (Alicat Scientific) with uncertainties of ±1.0% full scale were used to control flow rates from
individual streams. The volume fraction of methane $X_f$, the mean exit velocity of fuel jet $U_j$, and the coflow air velocity $U_{air}$ were adjusted to allow different flame attachment locations. The fuel jet was ignited to form a laminar jet diffusion flame by a burning torch. In addition, in experiments of downward flame propagation, an electric heating wire with diameter of 0.35 mm was used to ignite jets at about 130 mm above the nozzle. A schlieren setup was utilized for flow visualization. A digital camera (Point Grey, GS3-U3-41C6C-C) with 4,000,000 pixels per frame was employed for both direct (9–186 fps) and schlieren photographs (60–250 fps) of flames.

The velocity field near the flame base was measured by a particle image velocimetry (PIV) system with a 5 W CW semiconductor laser (SM-SEMI-5 W) at 532 nm as a light source. Silicon oil droplets of approximately 1 μm in diameter were supplied as seeding particles in the coflow air stream. Particle images were recorded by a high-speed camera (FASTCAM SA-Z) with a resolution of $1024 \times 1024$ pixels at 1000 fps and exposure time of 0.5 ms. The camera was equipped with an intensifier (Lambert) and a Nikon 100 mm, f/5.6 lens, creating a $37 \text{ mm} \times 37 \text{ mm}$ field of view for the experiments. A fixed interrogation spot (32 pixels) was used in PIV analyses.

**Numerical method**

The laminar CH$_4$/air diffusion flames were simulated with a two-dimensional steady axisymmetric model. Conservation equations of the mass, momentum, energy and species in the cylindrical coordinates ($r, x$) were discretized using the finite volume method. The SIMPLEC scheme was utilized to deal with the pressure-velocity coupling. Since it has been shown that the radiative heat from flame base has no significant direct effects on the burner.
wall temperature and the stability of methane jet diffusion flames from laminar to turbulent (Robson and Wilson 1969), and structures of very small laminar jet diffusion flames (Cheng et al., 2006; Gao et al., 2017), the radiative effects were neglected in our modeling.

A one-step global reaction mechanism model based on representative heat release of the chemical system was adopted. Provided that such one-step overall reaction model may not allow resolution of a detailed flame structure (Won et al. 2002), it can still reasonably describe the thermal and hydrodynamic fields (Kim et al. 2002) and the stoichiometric laminar burning velocities for mixtures (Kim et al. 2006). Hence, changes in the stabilization position of flame base, and heat losses by conduction and local convection in different cases can be reasonably captured here.

In this study, three sets of simulations were carried out for $X_f = 0.34$. For the first set, various thermal conditions were imposed on the burner wall, to mainly examine the effects of heat loss by conduction from the flame base to the burner wall on the attached flame stabilization. The burner wall was set as adiabatic, 273, 373, 473, 573, 673, 773 K, respectively, at $U_j = 4.0 \text{ m/s}$, $U_{air} = 0.05 \text{ m/s}$. For the second and third sets, the jet velocity ($U_j$) and coflow air velocity ($U_{air}$) were changed, respectively, to mainly consider influences of local convection on the stabilization of attached flame, $U_j$ ranging from 0.5 m/s to 5.0 m/s at $U_{air} = 0.05 \text{ m/s}$, $U_{air}$ varying from 0.05 m/s to 0.25 m/s at $U_j = 0.5 \text{ m/s}$, both the above two kinds of calculations using a fixed burner wall temperature of 273 K.

The computational domain, mesh and boundary conditions are shown in Figure 2. The computational dimensions of 100 mm ($x$) × 25 mm ($r$) are 31- and 8-fold the fuel nozzle diameter in axial and radial directions, respectively. The fuel nozzle exit is placed 20 mm downstream from the inlet boundary. The thickness of the burner wall is 0.5 mm, which is consistent with the experiment. The domain was divided into 360 and 122 cells in axial and radial directions, respectively. Non-uniform grids were constructed in both $x$ and $r$ directions with a minimum grid size of 0.05 mm, and stretch ratio of 1.05. The grid independence has been checked by comparing the results of doubled mesh numbers. A uniform velocity (using mean velocity) and temperature (300 K) profile was prescribed as the inlet boundaries for both fuel and coflow air. The outlet and side boundaries of the computational domain were placed far away the nozzle exit and the centerline, respectively, on which pressure outlet and symmetric boundary conditions were applied, respectively. For the burner wall surfaces, no-slip condition was applied.

**Results and discussion**

*Propagation characteristics of the diffusion flame base*

Photographs of jet diffusion flames (without coflow) with various methane volume fractions ($X_f$) are shown in Figure 3. For the attached flames, the vertical distance between the flame base and the nozzle exit gradually increases with decreasing $X_f$. Note that the flame base extends to even below the nozzle (cf. red circle in Figure 3a) due to a preferable mixing condition offered by fuel gas for the surrounding air. As $X_f$ decreases to a critical value, i.e. $X_f = 0.32$, flame lifting takes place through mild oscillation, eventually resulting in a considerable increase of the vertical distance. A triple structure can be seen in Figure 3c at the
lower part of the laminar lifted flame. As the vertical distance decreases, the lean premixed flame wing gradually decays before completely vanishing.

The local gas flow velocity \( (U_G) \) at flame base was obtained by PIV. Typical particle scattering image capturing the nozzle rim and flame zone is shown in Figure 4. The boundary of the particle region near the reaction layer shown in Figure 4 represents the
Because the seeding particles (silicon oil droplets) evaporate at about 600 K (Hirota et al. 2007). According to Upatnieks et al. (2004), the lowest point of isotherm is located just ahead of the flame base, where the axial gas flow velocity can be treated as the local flow velocity at flame base ($U_G$). Figure 5 shows the measured velocity field near flame base at $U_j = 1.05$ m/s, $X_f = 0.38$ for attached case. It can be clearly observed that gas flow velocities around the hot zone (dark region in which there is no vectors) are increased by buoyancy, and the surrounding air is entrained into this zone. At present work, the local gas flow velocity at flame base, $U_G$, was experimentally evaluated using the average of two velocity vectors (at location A and B) located at the upstream boundary of flame base in
velocity field shown in Figure 5. The axial velocities at points A and B are 0.06 m/s and 0.075 m/s, respectively, the difference is small.

After ignition at a further downstream location of nozzle, a well-defined laminar flame front is expected to propagate through the fuel/air mixing layer. As the axial distance decreases, this mixing layer gradually becomes narrower. Propagation speeds of tribrachial (triple) flames in laminar non-premixed jets were measured using similar methods by Ko and Chung (1999) and Lee et al. (2003b). Direct and Schlieren photographs presented in Figure 6 show the evolution of downwardly propagating flames that eventually stay attached (Figures 6a1, 6a2) and lifted flames (Figures 6b1, 6b2), respectively, from which propagation speeds can be obtained. When the flame base is far away from the nozzle, it exhibits a very clear tribrachial structure (Figures 6a1, 6b1). While the radial distance between the RPF (rich-premixed flame) and the DF (diffusion flame) branches continues to decrease, the LPF (lean-premixed flame) wing gradually disappears during the propagation process. These structural changes in flame base can be attributed to the change in mixing level of fuel/air streams with decreasing axial height of flame base (hence narrowing mixing layer) along the propagation trajectory.

Evolution of flame base location (the axial distance between the flame base and the burner exit) are plotted in Figure 7 for various methane volume fractions (Figure 7a), mean

\[ X_f = 0.38, \ U_j = 1.05 \text{ m/s.} \]
exit velocities (Figure 7b) and coflow velocities (Figure 7c). For $X_f = 0.30$ and 0.32 in Figure 7(a), $U_j = 2.74$ m/s and 2.84 m/s in Figure 7(b), and $U_{\text{air}} = 0.30$ m/s and 0.32 m/s in Figure 7(c), lift-off (denoted L.O.) occurred as the flames stop to propagate, while under other conditions attached flames appeared eventually. The results illustrate that the general behaviors of flame attachment and liftoff at above different conditions are qualitatively the same. As seen in Figure 7, for attached flames, when $X_f > 0.34$ (Figure 7a), $U_j < 1.92$ m/s (Figure 7b), and $U_{\text{air}} < 0.10$ m/s (Figure 7c), the flame base location decreases linearly with time, which is consistent with the results for methane jets (Ko and Chung 1999). While as $X_f$ decreases to 0.34 (Figure 7a), $U_j$ increases to 1.92 m/s (Figure 7b), and $U_{\text{air}}$ increases to 0.10 m/s (Figure 7c), the flame base location decreases nonlinearly. In particular, as the flame base approaches to the stabilization position, the slope of data near liftoff region gradually collapse to zero ($X_f \leq 0.32$ in Figure 7a, $U_j \geq 2.74$ m/s in Figure 7b, $U_{\text{air}} \geq 0.30$ m/s in Figure 7c), which is because either the laminar burning velocity drops due to the fuel dilution level (Figure 7a), or the local gas flow velocity increases with the jet (Figure 7b) or
coflow velocity (Figure 7c) that introduces a new velocity balance at the liftoff location. Such nonlinear evolution of flame base location were also reported for propane jets (Ko and Chung 1999). Besides, the duration of flame propagation for the attached flames is much less than that of the lifted flames, indicating the higher propagation speed ($S_d$, the difference between the maximum burning velocity of flame base and the local flow velocity $U_C$) for flame attachment compared to lifted flames. The tendency of flame base location and the duration of flame propagation are mainly influenced by the level of fluid mixing and the local gas flow velocity at flame base.

From the history of flame base location (Figure 7), the instantaneous flame propagation speed ($S_d$) can be calculated. The local gas flow velocity ($U_C$) at flame base was measured using PIV. Meanwhile, such local gas flow velocity has been successfully predicted using the similarity solution for velocity in laminar cold jets (free/coflow jets) (Lee and Chung 1997; Lee et al. 2003a) with a reasonable accuracy (Lee et al. 2003a). Shown in Figure 8 are the flame propagation speed at stabilization position, and the local gas flow velocity ($U_C$) at flame base from PIV and similarity solution in terms of $X_f$ (Figure 8a), $U_j$ (Figure 8b), and $U_{air}$ (Figure 8c).

For the laminar-lifted flame with $X_f = 0.32$ (Figure 8a), $U_j = 2.74$ m/s (Figure 8b), and $U_{air} = 0.30$ m/s (Figure 8c), $S_d$ is zero, as a result of primary stabilization mechanism of such flames (Chung and Lee 1991; Lee and Chung 1997; Lee et al. 2003a). However, $S_d$ increases
for the attached flames with $X_f > 0.32$ (Figure 8a), $U_j < 2.74$ m/s (Figure 8b), and $U_{air} < 0.30$ m/s (Figure 8c), indicating that the burning speed (the sum of $S_d$ and $U_G$) is larger than the local flow velocity at flame base. Such increase of $S_d$ becomes more significant with the increasing $X_f$ (Figure 8a), and decreasing $U_j$ (Figure 8b) and $U_{air}$ (Figure 8c). Note that $S_d$ is about 0.74 m/s at $X_f = 1$ as seen in Figure 8(a), by adding it to $U_G$, obtaining a burning speed much larger than the stoichiometric laminar burning velocity of methane/air mixture (0.40 m/s (Law 1993)). It has been substantiated experimentally and theoretically for methane that the burning velocity of flame base is in a range of 0.56–0.96 m/s (Ko and Chung 1999). The increase from the fundamental laminar burning velocity is due to flame stretch and mixture fraction gradient (Ko and Chung 1999; Lee et al. 2003b). It should be noticed that as the local flow velocity is not balanced by the maximum burning velocity at flame base for laminar attached non-premixed flames, the propagation of partially premixed flame in mixing layer is eventually ceased due to flame attachment.

The thickness of the fuel/air mixing layer is defined as the radial width of the flammable zone near the flame base (Lewis and Bernard, 1987). Figure 9 plots thickness of the fuel/air mixing layer $\sigma$ at the flame stabilization location for various $X_f$, $U_j$ and $U_{air}$. The value of $\sigma$ was calculated using the approximate solution for the fuel concentration $Y_F$ with and without coflow (Lee et al. 2003a). It is found that, as the flame base location increases by increasing $U_j$ (blue data), increase of $\sigma$ is promoted due to higher gradient of radial velocity that promotes momentum transport. As the decrease of $X_f$ was used to increase the flame
Figure 9. Thickness of the fuel/air mixing layer near flame base at various flame stabilization locations ('L. O.' denotes liftoff).

bottom height (black data), two competing effects emerge: (1) fluid density is lower such that given the same $U_j$ the overall inertia is smaller; (2) radial gradient of fuel concentration is smaller such that fuel diffusion flux is weaker. For the flow conditions of investigation in this study, where jet velocity is half to an order of magnitude larger than the coflow velocity (or without any coflow), the mixing is dominated by the shear induced by the central jet. Therefore, the fluid density effect plays a dominating role so that $\sigma$ increases as $X_f$ decreases. As the coflow velocity is gradually added to achieve various flame bottom height (green data in Figure 9), flow shear slightly decreases due to the coflow velocity approaching to the jet velocity. The mixing layer hence becomes thinner (the left half of green data before L.O.). Interestingly, as liftoff occurs, $\sigma$ jumps back to a higher value (see green data near L.O.), indicating that the local hydrodynamic mixing may as well be altered by the liftoff itself.

More importantly, the $\sigma$ values in Figure 9 ranges from 1.1 to 1.5 mm for nozzle-attached flames, larger than that within 0.6–0.8 mm found in the numerical results (Takahashi and Katta 2000a, 2000b), while still much less than the minimum quenching distance of laminar methane premixed flame propagating through a sufficiently small passageway (2.5 mm (Barnett and Hibbard, 1959)).

Local extinguishment caused by heat losses does not only pertain to premixed flames, it is likely responsible for the phenomenon in laminar attached non-premixed flames where the downward propagation of partially premixed flame within the mixing layer at flame base is ceased.

The above part for flame propagation and stabilization intends to first confirm with evidences of the past observation, which serves as the building block of this work. Nonetheless, the analyses that follow could not have been performed without such data, especially the velocimetry data. Those following analyses further speak to the role of balance theory and propagation in flame stabilization and offered a new perspective.

Since the radiative effect has little influence on the burner wall temperature and the stability of methane jet diffusion flames from laminar to turbulent (Lamige et al. 2014), characteristics of heat losses by conduction to the burner wall, and local convection are discussed in the present work.
Figure 10. Heat release rate (HRR, J/m$^3$s) and stoichiometric mixture fraction (black solid line) contours for $U_j = 4.0$ m/s, $U_{air} = 0.05$ m/s at various burner wall conditions: (a) adiabatic; (b) 273 K; (c) 373 K; (d) 573 K; (e) 773 K.
Heat loss characteristics of the flame base

The computed heat release rate (HRR) and stoichiometric mixture fraction (black solid line) contours at \( U_j = 4.0 \text{ m/s}, \ U_{\text{air}} = 0.05 \text{ m/s} \) for (a) adiabatic (b) 273 K (c) 373 K (d) 573 K and (e) 773 K as burner wall conditions are presented in Figure 10. The conductive heat transfer between the flame base and the burner rim can be adjusted through changing the thermal boundary condition of the burner wall. The coordinates of flame base are denoted using \( H_a \) and \( R_0 \), respectively, in \( x \) and \( r \) directions based in the center of burner exit. While the conductive heat loss to the fuel tube is neglected, the calculated flame attaches to the outer surface of the burner wall \( (H_a = -0.47 \text{ mm}), \) based on the lowest axial position of the 0.1 maximum HRR (Xu et al. 2018)) shown in Figure 10(a), which means the partially premixed flame at flame base can propagate along a much narrower mixing layer. It can also be concluded from Figure 10(a) that the heat loss by local convection has little effect on the flame attachment at a case without coflow. On the contrary, considering the conductive heat loss by assuming a fixed burner wall temperature leads to a slightly detached flame from the nozzle exit by about 0.67 mm seen in Figure 10(b), which suggests that a critical mixing layer thickness in which the local partially premixed flame can sustain and the quenching is mainly due to the heat loss by conduction of burner wall. The thickness of this mixing layer depends on the fuel type, jet and coflow velocity, burner material, initial temperature of fuel and coflow streams and so on. Moreover, as the burner wall temperature increases, the flame attachment point gradually approaches to the burner wall surface as displayed in Figure 10(b)–(e). While the stoichiometric lines in Figure 10(b)–(e) are almost identical, the higher wall temperature facilitates a low flame base location by shortening the pre-heat zone. Given that the mixing condition is the same, a flame base closer to the burner wall further restricts the scale of hydrodynamic mixing in front of the flame, leading to a slightly narrower reacting zone (cf. Figure 10(e)). The flame base location shall correspond with a length scale \( L_H \sim U_G \tau_c \) along the stoichiometric line; \( \tau_c \) is the summation of fluid preheating time and the characteristic chemical time pertaining to the one-step global reaction.

Figure 11 shows the heat release rate (HRR) distributions and stoichiometric mixture fractions (black solid line) at various coflow air velocities \( (U_{\text{air}}) \) for \( T_{\text{wall}} = 273 \text{ K}, \ U_j = 0.5 \text{ m/s} \). Since the local gas flow velocity \( (U_G) \) increases with \( U_{\text{air}} \) according to the similarity solution in laminar coflow jets (Ko and Chung 1999), heat loss by local convection increases with \( U_{\text{air}} \). From Figure 11(a), the flame attaches to the axial position at \( H_a = 0.50 \text{ mm} \) (based on the lowest axial position of the 0.1 maximum HRR (Xu et al. 2018)). With increasing \( U_{\text{air}} \), the flame attachment point gradually rises as shown in Figure 11(b)–(e). This is because the larger thermal inertia accompanied with the higher local flow velocity, prolonging \( \tau_c \) and hence the leading length of mixing layer. Besides, it can be clearly observed that the stoichiometric mixture fraction contour (black solid line) gradually moves onto the top of the burner wall as \( U_{\text{air}} \) increases because the back diffusion of fuel stream is suppressed, and hence resulting in a higher location of the attachment point. In addition, variations of the flame attachment point and the stoichiometric mixture fraction contour with mean exit velocity \( (U_j) \) are similar to those shown in Figure 11, respectively, while the mixing process of fuel/air and the flame base response more sensitive to the coflow.

It should be noted that the thermal quenching due to the heat loss by conduction to the burner wall, as well as the increased thermal inertia of the local incoming flow are
Figure 11. Heat release rate (HRR, J/m$^3$s) and stoichiometric mixture fraction (black solid line) contours for $T_{wall} = 273$ K, $U_j = 0.5$ m/s at various $U_{air}$: (a) 0.05 m/s; (b) 0.10 m/s; (c) 0.15 m/s; (d) 0.20 m/s; (e) 0.25 m/s.
responsible for a partially premixed flame to cease propagation and ‘attached’ in proximity of the burner in the mixing layer.

Consider a small region at attached flame base, the temperature of this zone is assumed to be $T_f$. The heat fluxes by thermal conduction $q_{\text{cond}}$, and local convection near the laminar attached diffusion flame base $q_{\text{conv}}$, are written as:

$$q_{\text{cond}} = KdT/dl \approx K(T_f - T_{\text{wall}})/l$$

(1)

$$q_{\text{conv}} = U_G\rho_fC_p(T_f - T_u)$$

(2)

where $K$ is the thermal conductivity, $T_{\text{wall}}$ is the burner wall temperature, $T_u$ is temperature of the incoming flow, $l$ is the distance between the burner wall and the flame base, $\rho_f$ is the density of the mixture at temperature of $T_f$, and $C_p$ is the constant pressure specific heat.

The heat fluxes from the flame base, by conduction to the burner ($q_{\text{cond}}$) and by local convection ($q_{\text{conv}}$) are plotted in Figure 12 for the various boundary conditions of burner wall, jet exit velocities, and coflow velocities. For an adiabatic wall, the local convection mainly dominates the heat loss near the flame base. As shown in Figure 12(a), with increased $T_{\text{wall}}$ the conductive heat loss between the flame base and the burner rim ‘increases’. As $q_{\text{cond}}$ is proportional to both $(T_f - T_{\text{wall}})$ and $\Gamma^1$ (cf. Eq. (1)), the competition between these two terms is the critical factor for conductive heat loss. Since the effect of $T_{\text{wall}}$ on $(T_f - T_{\text{wall}})$ is linear but on $\Gamma^1$ is exponential due to characteristic time of chemistry, $\Gamma^1$ outtrumps $(T_f - T_{\text{wall}})$ for their effect on $q_{\text{cond}}$ leading to an increasing $q_{\text{cond}}$ with increasing $T_{\text{wall}}$. Also demonstrated by the smaller $H_s$ for the case of $T_{\text{wall}} = 773$ K in Figure 10(e), such a small $l$ promotes propagation of local partially premixed flame at flame base toward a narrower mixing layer, regardless slightly larger conductive heat loss (cf. Figure 12(a), $T_{\text{wall}} = 773$ K).

From the local heat losses near flame base at various jet exit velocities shown in Figure 12(b), $q_{\text{conv}}$ increases with $U_j$. Therefore, sustaining the local partially premixed flame needs a thicker mixing layer, resulting in the increase of $H_s$. Figure 12(c) presents the local heat losses at various coflow velocities. It can be seen that the tendency of $q_{\text{conv}}$ is similar to that in Figure 12(b), but its slope is larger, causing the flame base stabilizing at a higher location, which is consistent with the experimental and numerical results. Whereas for the attached flames, the thickness of mixing layer ($\sigma$) slightly decreases with $U_{\text{air}}$ (see Figure 9). The decreasing of $q_{\text{cond}}$ with $U_{\text{air}}$ (Figure 12c) is as a result of increasing $l$ and lower $T_s$ probably responsible for persistent flame stabilization in this case. Note that $q_{\text{conv}}$ is quite sensitive to $U_{\text{air}}$ and at some point exceeds the $q_{\text{cond}}$ in coflow flames. It implies that the stabilization of nozzle-attached diffusion flame is more sensitive to and easily dominated by the coflow air.

It should be noticed from Figure 12 that $q_{\text{cond}}$ is larger than its corresponding $q_{\text{conv}}$ except for several cases for $U_{\text{air}} \geq 0.15$ m/s. Moreover, the fraction of $q_{\text{cond}}$ (defined as $q_{\text{cond}}/(q_{\text{cond}} + q_{\text{conv}})$) shown in Figure 12 (olive solid symbols) stays mainly at 0.50–0.60 with certain extreme cases of 0.37 or 0.70. Consequently, the conductive heat loss to the burner wall plays a relatively important role to the stabilization of nozzle-attached diffusion flame without (or with a small amount of) coflow air. As the coflow air velocity increases, the heat loss by local convection gradually becomes the significant factor of flame stabilization.

To further understand how the thickness of mixing layer depends on other characteristic parameters in such a problem, the following assumptions are made for the small region at attached flame base for further discussions: (1) the width of this region is taken to be the
Figure 12. Heat losses by conduction and local convection of the flame base for: (a) various wall thermal conditions; (b) various jet velocities; (c) various coflow velocities.
thickness of mixing layer ($\sigma$), and the surface area of this region normal to the page is unity; (2) $\delta$ represents the flame thickness; (3) $T_{wall} = T_{u}$; (4) the radiative heat transfer from the flame base is neglected.

Applying the quenching criteria of Williams (1985) that the heat released by chemical reaction is nearly balanced with the heat loss, and following Friedman’s approach (1948), an energy balance equation is written as:

$$\dot{Q}'' V = (q_{\text{cond}} + q_{\text{conv}})(\sigma.1)$$  \hspace{1cm} (3)

where $\dot{Q}''$ is the volumetric heat production rate, $V$ is the volume of reaction zone at flame base. Assuming a simple overall reaction, $\dot{Q}''$ can be related to the fuel mass production rate, i.e. $V = \delta.1.1$ (Turns 2000), where $\dot{m}_F \approx \rho_u S_L^2 / [-2\alpha(j+1)]$, $\rho_u$, $S_L$, and $\alpha$ are the density of unburned gas, the laminar burning velocity at the flame base and the thermal diffusivity, respectively. The heat of combustion of the fuel is defined as $\Delta h_f = (j+1)C_p(T_f - T_u)$.

From Eqs. (1), (2), and (3), the thickness of mixing layer at flame base, $\sigma$, can be obtained:

$$\sigma = \rho_u C_p S_L / \left[ K + \rho_f U_G C_p I \right]$$  \hspace{1cm} (4)

Figure 13 shows such variation of thickness ($\sigma$) of the fuel/air mixing layer at various local gas flow velocities (black line, Eq. (4)) for different laminar flame speed together with the experimental (blue symbols) and simulation results (olive symbols). It can be seen that results of experiment and simulation are in acceptable agreement with that of the theory with a primary trend of $\sigma \sim U_G^{-1}$ for fixed $S_L$ (while $K \ll \rho_f U_G C_p I$ in our cases). The scattering experimental data suggest that given similar $U_G$, $S_L$ can be very different. The value of $S_L$ is influenced by the dilution, jet velocity, and co-flow velocity in the experiment. As such, the comparison shall be made with theory for a range of various $S_L$. Besides, the effect of radical transport may be present in the experimental data, i.e. altering the $S_L$ and increasing the data scattering. Such effect is not considered by either our simulation or our theoretical model because that is beyond the scope of our discussion. Larger $S_L$ corresponds to larger $s$ for a given $U_G$.

for a given $U_G$. From Figure 13, as $U_G$ increases, e.g. by increasing the fuel jet velocity or coflow air velocity, or $S_L$ decreases, e.g. by adding some dilute components, the critical mixing layer ($\sigma$) will decrease. At this time, a larger $\sigma$ is needed to maintain the combustion, therefore corresponding to a farther downstream location of nozzle in which flame base stabilized (i.e. higher $H_a$).

**Conclusions**

Experiments and simulations on the stabilization mechanism of the nozzle-attached flames in laminar non-premixed jets were conducted. Experimental evidence provided for stabilization
Mechanism of the laminar attached flame was contrary to the balance between the local flow velocity and the burning speed, indicating that the propagation of partially premixed flame within the mixing layer at flame base is inhibited due to flame attachment. The thickness of the fuel/air mixing layer near the attached flame base was found to be in a range of 1.1–1.5 mm, less than the minimum quenching distance. Besides, results of the numerical simulation show that, the partially premixed flame at flame base can propagate through a much narrower mixing layer as the fuel tube is nearly adiabatic. On the contrary, with considering the conductive heat loss, a critical thickness of the mixing layer (in which the local partially premixed flame can maintain) exists near the flame base. Furthermore, the heat loss by conduction plays a relatively important role to flame stabilization without (or with a small amount of) coflow air. With coflow air velocity increasing, the heat loss by local convection gradually plays a significant role in flame stabilization. In addition, a simplified analysis is provided based on the balance between the heat released by chemical reaction and the heat lost by conduction and local convection, deriving a correlation for the clear dependence of the thickness of the fuel/air mixing layer on the local jet velocity and the laminar flame speed. From such relation, the flame base stability can be reasonably explained and predicted.

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