Effects of Schmidt number on Non-monotonic Liftoff Height Behavior in Laminar Coflow-jet flames with Diluted Methane and Ethylene

Kyu Ho Van¹, Su Hyeon Oh², Min Suk Cha³, Chun Sang Yoo²*, Jeong Park¹*, Suk Ho Chung³

¹ Department of Mechanical Engineering, Pukyong National University, Busan, Korea
² Department of Mechanical Engineering, Ulsan National Institute of Science and Technology, Ulsan, Korea
³ Clean Combustion Research Center (CCRC), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

Abstract
Stabilization characteristics of laminar lifted jet flames in a coflow were investigated experimentally to elucidate the effect of Schmidt number in methane and ethylene fuels diluted with N₂, He, and Ar. A non-monotonic (decreasing and then increasing) liftoff height (H_L) behavior with jet velocity (U₀) was observed previously for methane fuel diluted with N₂. To further elucidate the fuel Schmidt number (Sc_F) effect in exhibiting such a non-monotonic (U-shaped) behavior, various diluents (N₂, He, and Ar) were added to the fuel streams and methane and/or ethylene fuels were used. The result showed three flame types in terms of Sc_F and fuel density; nozzle-attached flame, stationary lifted flame, and oscillating flame. Among stationary lifted flames, two distinct H_L behaviors with U₀ were observed; monotonic and non-monotonic H_L behaviors. A critical Schmidt number (Sc_F,cr1) existed over which monotonically increasing behavior was observed. A second critical Schmidt number (Sc_F,cr2) also existed such that U-shaped behavior was observed for Sc_F,cr2<Sc_F<Sc_F,cr1. An oscillating lifted flame was observed for Sc_F<Sc_F,cr2. The oscillating and stationary lifted flames can be categorized in terms of the density differences among the fuel, air, and burnt gas. For the increasing H_L cases (including the increasing regime in U-shaped behavior), H_L behavior can be characterized in terms of Sc_F, the density difference between fuel and air, Sc_F,cr1, and U₀. While the decreasing H_L regime in the U-shaped behavior can be characterized with Sc_F and/or the Richardson number (defined based on the density difference between fuel and air). Oscillating flames were observed with the frequency range of 2.1–2.7 Hz by the repetitive action of positive (by burnt gas) and negative (when the fuel heavier than air) buoyancies.

Keywords: Lifted flame; Coflow jet; Schmidt number; Buoyancy; Edge flame
1. Introduction

Lifted flame characteristics in nonpremixed jets are interesting phenomena for the understanding of fundamental physics for flame stabilization and the safety of practical combustion systems. In a laminar nonpremixed jet, a lifted flame has a tribrachial (triple) edge structure, having a lean and a rich premixed flame wings and a trailing diffusion flame, all extending from a tribrachial point, which is located along a stoichiometric contour [1–6]. The stabilization mechanism has been explained based on the balance mechanism between edge flame speed and local axial velocity. An edge flame speed depends on various parameters including mixture strength, fuel concentration gradient, flame curvature, strain rate, flow redirection effect, and Lewis number [7–13]. A local flow speed can be influenced by a buoyancy effect [12, 13] through the entrainment of ambient air. An oscillation of lifted flame has also been observed which has been attributed to a buoyancy effect [14–17].

An analysis based on similarity solutions for velocity and fuel concentration in a free jet assuming the region between a nozzle and lifted flame edge as a cold jet, showed that a lifted flame is stable (unstable) for the Schmidt number of fuel, $Sc_F$, larger (smaller) than unity [1, 2]. For $Sc_F > 1$ (e.g., propane and butane fuels), the liftoff height, $H_L$, increased monotonically with jet velocity, $U_0$, and has an excellent correlation in terms of $Sc_F$ and $U_0$ [1]. Note that these lifted flames were stabilized in the far field of a jet when sub-millimeter size nozzles were used. When relatively large size nozzles of $O(10 \text{ mm})$ in diameter were used, lifted flames were stabilized in two distinct regions of jets: developing and developed regions. In such cases, the buoyancy played an important role for lifted flame stabilization [14].

Stable lifted flames could exist even for $Sc_F < 1$ in diluted methane jet flames [18, 19]. For $N_2$-diluted methane jet flames with $Sc_F < 1$, a stationary lifted flame could exist in the developing region of a jet [12]. Recent experimental and numerical study [13] on laminar lifted flames in a coflow with nitrogen-diluted methane ($Sc_F < 1$) exhibited two distinct behaviors in
liftoff height as the fuel jet velocity increases depending on fuel mole fraction; a monotonically increasing \( H_L \) behavior and a decreasing and then increasing non-monotonic \( H_L \) behavior (hereafter termed U-shaped behavior). The former was observed in the jet-developing region, while the latter in the jet-developed region. It has been shown that the U-shaped behavior was controlled by the relative importance between the jet and buoyancy-induced momenta. It is expected that the fuel Schmidt number could play an important role in exhibiting such a U-shaped behavior, however, in the previous works [12, 13], the Schmidt number variation was small.

Motivated by this, the present study systematically varied the Schmidt number to identify the effect on the U-shaped behavior in laminar nonpremixed coflow jets. The fuel stream with 30% \( \text{CH}_4 \)/70% \( \text{N}_2 \) was taken as a baseline case, where a U-shaped behavior was observed previously [13]. Then, the fuel Schmidt number was varied in the range of 0.70–1.34 by (1) diluting the fuel stream with \( \text{N}_2 \), Ar, and He and (2) adjusting the mixture composition of fuels (methane and ethylene), through which the fuel stream density also varied. The existence of U-shaped behavior is reported in terms of the fuel Schmidt number and the density differences among the fuel, coflow air, and burnt gas. Additionally, an oscillating lifted flame regime was identified.

2. Experiment

The apparatus consisted of a coflow jet burner, a flow control system, and a visualization setup, as schematically shown in Fig. 1. The fuel stream was composed of methane and/or ethylene (> 99.99 % purity) diluted with \( \text{N}_2 \), He, and Ar (99.95 % purity). This can effectively vary the Schmidt number of fuel along with the fuel stream density (\( \rho \)). The oxidizer stream was air. The inner diameter \((D)\) and length of the fuel tube were 4 and 600 mm, respectively, for the flow inside the tube could be fully developed. A cylindrical quartz tube with 93 and 400
mm in inner diameter and height, respectively, was used for the coflow air, and a series of fine meshes and a ceramic honeycomb were installed to ensure a uniform coflow velocity, $V_{co}$, at the exit to the quartz cylinder, which was fixed to 7 cm/s throughout the experiment.

![Fig. 1. Schematic of the experimental setup.](image)

The flow rates were controlled by mass flow controllers. The nominal accuracies at the full-scale flow rates were within 1.0 %. Experiments were conducted in the range of $39.8 \leq Re_D \leq 224.0$, where $Re_D$ is the Reynolds number based on $D$. The liftoff height was defined as the axial distance between the brightest point of flame edge and the nozzle exit, which was measured from the images from a digital camera (16.1 megapixel with 60 fps) attached to a two-axis translation stage. A Matlab-based software was used and details of image processing were reported previously [13, 16, 17].

The fuel stream composition was varied by the diluents of N$_2$, He, Ar and their mixtures in order to vary the fuel Schmidt number and fuel density. For methane jets, the mole fraction in the fuel stream was fixed at $X_{CH_4} = 0.3$ and $X_i = 0.7$ ($i = $ He, N$_2$, and Ar and their mixtures), yielding the Schmidt number range of 0.698 to 0.871. Here, $X$ is the mole fraction. To further elaborate the effect of the Schmidt number on liftoff height behavior, methane and ethylene mixture fuels were tested, while maintaining the adiabatic flame temperatures ($T_{ad}$) having a similar range as that for the methane flames by adjusting the fuel mole fraction in the fuel stream. The test conditions are summarized in Table 1 with $T_{ad}$ calculated from the Chemkin
Pro package [20] with GRI 3.0 Mech [21]. The transport properties such as kinetic viscosity, \( \nu \), and fuel mass diffusivity into air stream, \( D_F \), were calculated from an open-source program [22] to determine \( Sc_F = \frac{\nu}{D_F} \). The effective diffusivity of mixture fuel of methane and ethylene was determined from \( D_F = X_{CH4} D_{CH4} + X_{C2H4} D_{C2H4} \) [23].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>( X_F )</th>
<th>( \rho_F ) [kg/cm³]</th>
<th>( T_{ad} ) [K]</th>
<th>( Sc_F )</th>
<th>( \nu ) [cm²/s]</th>
<th>( D_F ) [cm²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>0.300</td>
<td>0.31 (( X_{He} = 0.70 )) - 1.33 (( X_{Ar} = 0.70 ))</td>
<td>1980 – 2080 (2020 at ( X_{He} = 0.35 ))</td>
<td>0.698 (( X_{Ar} = 0.70 )) - 0.871 (( X_{He} = 0.70 ))</td>
<td>0.157 (( X_{Ar} = 0.70 )) - 0.196 (( X_{He} = 0.70 ))</td>
<td>0.225</td>
</tr>
<tr>
<td>CH₄ + C₂H₄ (3:1)</td>
<td>0.230</td>
<td>0.30 – 1.43</td>
<td>1980 – 2100</td>
<td>0.742 – 0.967</td>
<td>0.155 – 0.202</td>
<td>0.209</td>
</tr>
<tr>
<td>CH₄ + C₂H₄ (1:1)</td>
<td>0.185</td>
<td>0.30 - 1.49</td>
<td>1970 – 2100</td>
<td>0.793 – 1.078</td>
<td>0.153 – 0.208</td>
<td>0.193</td>
</tr>
<tr>
<td>CH₄ + C₂H₄ (1:3)</td>
<td>0.155</td>
<td>0.30 – 1.53</td>
<td>1970 – 2110</td>
<td>0.853 – 1.198</td>
<td>0.151 – 0.212</td>
<td>0.177</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>0.135</td>
<td>0.29 – 1.56</td>
<td>1970 – 2120</td>
<td>0.932 – 1.335</td>
<td>0.150 – 0.215</td>
<td>0.161</td>
</tr>
</tbody>
</table>

**Fig. 2.** Direct images of typical lifted flames with \( U_0 \) for monotonically increased \( H_L \) in helium-diluted methane (a) and U-shaped \( H_L \) in nitrogen-diluted methane (b), and attached flames in argon-diluted methane (c) for \( X_F = 0.30 \) and \( V_{CO} = 7 \) cm/s.
3. Results and discussion

3.1. Overall features of lifted flame behavior

Direct images of laminar coflow flames of methane diluted with N₂, Ar, and He are shown in Fig. 2 in terms of jet velocity at $(X_{CH4}, X_{N2}, X_{He}, X_{Ar}) = (0.3, 0, 0.7, 0)$ (a), $(0.3, 0.7, 0, 0)$ (b), and $(0.3, 0, 0, 0.7)$ (c). Although not clear from the images, the lifted flame edges show tribrachial structure visible to the naked eye. With the He-dilution ($Sc_F = 0.871$), the liftoff height increases monotonically with the jet velocity (a), while the liftoff height exhibits a non-monotonic U-shaped behavior with the jet velocity (b) with the N₂-dilution ($Sc_F = 0.714$). With the Ar-dilution ($Sc_F = 0.698$) (c), the flame is attached to the nozzle.

For $0.698 < Sc_F < 0.709$, the lifted flame is not stationary and it oscillates for $U_0 = 16$ cm/s (movies in Supplementary Material (SM) 1). The oscillation maintains up to $U_0 = 20$ cm/s and the flame becomes nozzle-attached at $U_0 = 22$ cm/s. These behaviors are related to buoyancy effect and will be discussed later.

![Fig. 3. Variations in liftoff height with fuel jet velocity at various Schmidt numbers for methane flames diluted with N₂ and/or He or Ar.](image)

Variations in the liftoff height with increasing jet velocity at various $Sc_F$ are plotted in Fig. 3 with $X_{CH4} = 0.3$ for methane flames diluted with N₂, He, and Ar. The diluent volume fraction $Ω_j$ in the fuel stream (N₂ mixed with He or Ar) is defined as $Ω_j = X_j / (X_j + X_{N2})$ where $j$ denotes He or Ar. Since $X_{CH4} = 0.3$ and $X_j + X_{N2} = 0.7$, $Ω_{He} = 1.0$ corresponds to $X_{He} = 0.7$ and $X_{N2} = 0$ and $Ω = 0$ to N₂-dilution ($X_{N2} = 0.7$). For comparison, the jet developing length $Z_{free}$ is plotted...
with the black lines indicating the range of $Z_{\text{free}}$. Here, $Z_{\text{free}}/D = 0.0165 \times \text{Re}_D$, which was estimated from a free jet theory [24]. Thus, the axial distance $z < Z_{\text{free}} (z > Z_{\text{free}})$ corresponds to the jet developing (developed) region.

For small jet velocities, the buoyancy effect exerted by burnt gas dominates over convection, which can be represented by the Richardson number $\text{Ri} = (\rho F - \rho b)gD/\rho F U_0^2$, where $\rho b$ is the burnt gas density of stoichiometric mixture of fuel and air and $g$ is the gravitational acceleration. The range of $\text{Ri}$ is marked in the orange lines. The result shows that the Richardson number decreases appreciably with the jet velocity, implying that the buoyancy effect can be significant only at small jet velocities.

The result in Fig. 3 shows that the liftoff height versus jet velocity exhibits the U-shaped behavior for $0.709 \leq \text{Sc}_F \leq 0.748$ (with decreasing $H_L$ in large $\text{Ri}$ regime), nozzle-attached flame for $\text{Sc}_F = 0.698$, and monotonically increasing behavior for $\text{Sc}_F \geq 0.755$. This emphasizes the important roles of the Schmidt number and Richardson number on the liftoff height behavior. Although not shown, the lifted flame oscillates for $0.698 < \text{Sc}_F < 0.709$, (will be discussed later). These conditions were achieved with Ar as the diluent, which is heavier than coflow air, implying that lifted flame could be influenced by a negative buoyancy exerted on fuel in the downward direction [17].

**Fig. 4.** Effect of fuel Schmidt number and fuel stream density on lifted flame behavior for methane-diluted jet flames with $X_{\text{CH4}} = 0.3$. 


Recognizing the importance of fuel density, we further examine the overall behavior of lifted flame for methane diluted with N$_2$, He, and Ar in Fig. 4 in terms of the fuel Schmidt number and fuel density. There exists a critical Schmidt number, $Sc_F = 0.755$, over (below) which the liftoff height exhibits a monotonic (U-shaped) behavior. The lifted flame oscillation was observed when the fuel stream density is relatively large ($\rho_F > 1.09$ kg/m$^3$). Note that the air density is 1.18 kg/m$^3$ (at 25°C), which is close to the critical fuel density of 1.09 kg/m$^3$. This emphasizes the important role of negative buoyancy exerted on the fuel stream in generating flame oscillation. In summary, the behavior of lifted flame for methane ($Sc_F < 1$) has been influenced appreciably by the fuel Schmidt number as well as the buoyancy exerted on the fuel stream.

3.2. Regime Diagram on lifted flame behavior

We further extended the range of fuel Schmidt number by utilizing blended fuels of CH$_4$ and C$_2$H$_4$ (Table 1). The range of $T_{ad}$ was adjusted by varying the fuel mole fraction $X_F$, so that the positive buoyancy exerted by burnt gas was kept nearly the same as that of methane fuel case.

![Regime Diagram on lifted flame behavior](image)

Fig. 5. Regime diagram on lifted flame behavior in terms of fuel Schmidt number and fuel density. Fuel mole fractions were adjusted to keep the adiabatic flame temperatures to be in the same range as those of methane fuel.
A regime diagram is presented in Fig. 5 in terms of the Schmidt number and fuel density. The behavior can be classified into three regimes: monotonically increasing behavior of liftoff height with jet velocity (regime I), U-shaped behavior (regime II), and flame oscillation (regime III). The solid line between regimes I and II (II and III) corresponds to the first (second) critical Schmidt number, $Sc_{F,cr1}$($Sc_{F,cr2}$), changing the lifted flame behavior for fixed fuel densities. The best fit correlation is $Sc_{F,cr1} = 0.22 + 0.72 \times \rho_F$ ($Sc_{F,cr2} = -6.79 + 6.73 \times \rho_F$) with $R = 0.98$ (0.91). The cross-point of $Sc_{F,cr1}$ and $Sc_{F,cr2}$ lines is 1.05, which is sufficiently close to unity, such that the U-shaped behavior can be observed for $Sc_{F}<1$.

In regime I for $Sc_F > Sc_{F,cr1}$ with relatively small fuel density, jet momentum plays an important role for the stabilization of lifted flame such that the liftoff height increases with jet velocity. In regime II for $Sc_{F,cr2} < Sc_F < Sc_{F,cr1}$ with intermediate fuel density, the relative role of the buoyancy over convection in flame stabilization is important at small jet velocities, whereas the flame stabilization was controlled by jet momentum at large jet velocities [13], thus exhibiting the U-shaped behavior. In regime III for $Sc_F < Sc_{F,cr2}$ with large fuel density, the negative buoyancy by the fuel heavier than air plays an important role in triggering the flame oscillation [17]. In summary, as the fuel density increases (thereby $R_i$) at a specified $Sc_F$, the flame stabilization exhibited monotonic behavior (regime I) for small $\rho_F$, U-shape behavior for intermediate $\rho_F$, and flame oscillation for sufficiently large $\rho_F$ (especially larger than air density). The U-shaped behavior can only be observed for $Sc_F < 1$. As $Sc_F$ decreases, the range of $\rho_F$ for U-shaped behavior extends.
Fig. 6. Characterization of increasing liftoff height behavior with jet velocity (increasing range in U-shaped behavior is also included).

Fig. 7. Characterization for decreasing liftoff height in U-shaped behavior.

3.3. Characterization of liftoff height behavior

The liftoff height behavior in regime I and increasing range in the U-shaped behavior is characterized based on (1) the jet velocity $U_0$ scaled by stoichiometric laminar burning velocity $S_l^0$ according to the stabilization mechanism [1,2,5] and (2) the density difference ($\rho_{co} - \rho_F$) inducing positive buoyancy ($\rho_{co}$ being coflow air density), thereby increasing local flow speed and liftoff height.
The result is shown in Fig. 6 in terms of \((\rho_{co} - \rho_F)/\rho_F\) and \((U_0/S_{L0})\). The best-fit is \(H_L = 0.16 + 4.99 \times [((\rho_{co} - \rho_F)/\rho_F) \times (U_0/S_{L0}) \times Sc_F,cr1]^2.29 \times (Sc_F - 0.5)\) with \(R = 0.91\). The exponent \((Sc_F - 0.5)\) was chosen, because for the fuel with \(Sc_F < 1\), the liftoff height behaviors between the fuels having \(Sc_F < 0.5\) and \(Sc_F > 0.5\) are quite different based on the free jet theory [1,2,5]. This relation is valid only for \(Sc_F > 0.5\) and \((\rho_{co} - \rho_F) > 0\). An exceptional case is for \(\Omega_{He} = 1.0\), where the liftoff height decreased with the increase in \(Sc_F\) (Fig. 2), thus \(H_L\) deviates appreciably from the above correlation, as shown in Fig. 6. This may be attributed partly to differential diffusion effect of the very light molecule of He and large stoichiometric laminar burning velocity (SM).

For the decreasing liftoff height with jet velocity in the U-shaped behavior, the relative role of the buoyancy over convection in flame stabilization was emphasized for small jet velocities [13]. For N\(_2\)-diluted methane flames, \(Sc_F\) varied 0.710–0.714 (0.51% variation) while \((\rho_F - \rho_{co})\) varied 89%. The density difference \((\rho_F - \rho_{co})\) influences appreciably on the liftoff height (Fig. 3). Note that in the U-shaped regime, the difference \((\rho_F - \rho_{co})\) can be either positive or negative, as was shown in Fig. 7. Considering the importance of \((\rho_F - \rho_{co})\) and its sign, the liftoff height is correlated with a new Richardson number, \(Ri^* = |\rho_F - \rho_{co}|Dg/\rho_FU_0^2\). Note that \(H_L\) decreases with the increase in \(Sc_F\), which has been explained previously by the competition between buoyancy-induced and jet momenta [13]. For Ar-diluted cases (Fig. 7a), the best-fit is \(H_L = 4.68 \times Ri^*^{0.55}\) with \(R = 0.95\), otherwise \(H_L = -0.93 + 10.65 \times [Ri^*(1 - Sc_F/Sc_F,cr1)]^{0.30}\) with \(R = 0.94\) (Fig. 7b).
Fig. 8. Critical onset conditions of flame oscillation and stationary lifted flame in terms of density differences ($\rho_{co} - \rho_b$) denoting positive buoyancy and ($\rho_f - \rho_{co}$) denoting negative buoyancy by fuel stream.

The flame oscillation was previously shown to be attributed to the effects of competitive forces acting on the flow field by the positive buoyancy from burnt gas and negative buoyancy from the fuels, especially heavier than air ($C_3H_8$ and $n-C_4H_{10}$) [17], which corresponds to $Sc_F > 1$. Those critical onset conditions are marked as the dotted lines on Fig. 8 in terms of ($\rho_{co} - \rho_b$) and ($\rho_f - \rho_{co}$), demarking the regions of stationary lifted flame, oscillation, and flame extinction (marked as ext 1) regimes. These experimental data mainly with $C_3H_8$ and $n-C_4H_{10}$ fuels correspond to ($\rho_f - \rho_{co}$) > 0.04 kg/m$^3$ [17]. The range of ($\rho_f - \rho_{co}$) is appreciably extended (marked as the solid lines) for the present data by utilizing $CH_4$ and $C_2H_4$. The present data in Fig. 8 were, for simplicity, taken with those of $Sc_{F,cr1}$ (data with black circles indicating U-shaped behavior) and $Sc_{F,cr2}$ (data with black triangles showing flame oscillation) along with flame conditions with the interval of 10% dilution ratio. The present data are represented as three shaded regions identified as monotonic increasing liftoff height behavior (regime I), U-shaped behavior (II), and flame oscillation (III). In the overlapped shades of regimes I and II, the data with black thick triangles correspond to regime II, otherwise regime I. The solid line connecting the data of baseline case ($X_{CH4} = 0.3$ and $X_{N2} = 0.7$) near regimes I to II denotes extinction limit (ext 2) such that the flame extinguishes (ext 2) when ($\rho_{co} - \rho_b$) is reduced further, e.g., decreasing $X_{CH4}$ to 0.29 and $X_{N2} = 0.71$, otherwise the flame shows a stationary
lifted flame. Consequently, the map can be well explained by two parameters in Fig. 8: the density difference \((\rho_{\text{co}} - \rho_{b})\) representing the buoyancy due to burnt gas and the density difference \((\rho_{F} - \rho_{\text{co}})\) denoting the buoyancy due to fuel. Note that \((\rho_{F} - \rho_{\text{co}}) > 0\) results in a negative buoyancy on the cold coflow air, implying the downward direction of buoyancy force. While for \((\rho_{\text{co}} - \rho_{b}) > 0\), a positive buoyancy acts upwardly by the burnt gas.

Fig. 9. Direct images for cold (a) and reacting jets (b) in case of the occurrence of flame oscillation; \(X_{F,0} = 0.3, U_0 = 18\) cm/s, and \(\Omega_{Ar} = 0.5\).

To clearly identify the effect of negative buoyancy by the fuel stream, Mie scattering images with TiO\(_2\) seeding to coflow are shown in Fig. 9 for \(\Omega_{Ar} = 0.5\) with \(X_{F} = 0.3\) and \(U_0 = 18\) cm/s (movie in SM 3). For the cold jet, the fuel stream loses momentum as flowing downstream by the negative buoyancy and reaches a stagnation region, then flowing transverse direction and carried downstream by the coflow momentum. For the reacting flow, the lifted flame forms near the nozzle exit and oscillates (SM 2), implying that the flame oscillation is triggered by the competing effects between negative (by fuel) and positive (by burnt gas) buoyancies [17]. The frequency is in range of 2.1–2.8 Hz. In case of nozzle-attached coflow flames, typical flickering frequency due to buoyancy-induced instability is \(O(10\) Hz\) with nozzle diameter \(D = O(10\) mm\). While the oscillation frequencies for lifted flames are 3.0–4.5 Hz for N\(_2\)-diluted propane \((D = 11.1\) mm\) [14]
25, 26] and 2.1-2.8 Hz for the present diluted methane \((D = 4\text{mm})\), thus having similar range of frequencies. The average liftoff height increases with jet velocity as in [14]. The comparison of non-dimensional Strouhal number for methane flame is shown in SM 4, which we have varied the jet velocity. Note that the present data are limited because we have adjusted the Schmidt numbers to have similar adiabatic flame temperatures. The insensitivity of frequency can be partially attributed to the limited range of jet velocity in terms of the ratio of minimum to maximum as compared to those in [14]. The positive buoyancy by the burnt gas promotes the ambient air entrainment, increasing local flow speed. During the period of flame edge migrating downstream, the burning rate decreases as the fuel is accumulated between the nozzle and flame edge and the edge flame speed increases due to the reduction in fuel concentration gradient [5], leading to the decrease in the buoyancy toward downstream. Eventually, the flame edge starts to propagate upstream, increasing the burning rate by the consumption of the accumulated fuel, enhancing the buoyancy-induced entrainment and flow velocity toward upstream. Then the flame edge again starts to propagate downstream. This repetitive nature can explain the flame oscillation behavior.

4. Conclusion

Stabilization of laminar lifted coflow jet flames were studied experimentally by varying jet velocity and fuel Schmidt number along with the fuel density by diluting with N\(_2\), He, and Ar. The following conclusion could be made:

1) Three types of flame behavior were observed: nozzle-attached, stationary lifted, and oscillating lifted flames. For stationary lifted, two types of liftoff height behaviors were observed with jet velocity; monotonic increase and U-shaped behavior.

2) There existed first critical Schmidt number \(\text{Sc}_{F,cr1}\) over (below) which the monotonic increasing (U-shape) behavior was exhibited. The second fuel Schmidt number \(\text{Sc}_{F,cr2}\) existed below which the flame oscillated. In such cases \(\text{Sc}_F < \text{Sc}_{F,cr2}\) diluted with Ar,
the fuel stream is heavier than coflow air. These critical Schmidt numbers depended on the density difference between fuel and air. The increasing $H_L$ behavior with $U_0$ was correlated with $(\rho_{co} - \rho_F)/\rho_F$ and $U_0/S_{L0}$. The decreasing $H_L$ behavior was correlated with the Richardson number based on $(\rho_F - \rho_{co})$.

3) Flame regimes were identified in terms of density differences among the fuel, air and burnt gas.

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References


[23] F. Dinkelacker, B. Manickam, S. P. R. Muppala, Modelling and simulation of lean premixed turbulent methane/hydrogen/air flames with an effective Lewis number approach,
