On the Characteristics of Liftoff Heights in Laminar Lifted Flames of Methane in Coflow Jets

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1 Introduction

Laminar lifted non-premixed free and co-flow jet flames have been studied extensively to clarify the characteristics of flame stabilization, to develop laminar stretched flamelet model and to get the fundamental data for designing industrial burners [1-3]. It propagates along the stoichiometric contour due to the intrinsic nature of its leading edge that consists of lean and rich premixed flame wings and a trailing diffusion flame, all extending from a triple point. Thus, the stabilization mechanism is addressed to the balance between the tri-brachial flame speed and local axial flow velocity. Based on the similarity solutions of velocity and concentration in jets, a correlation of lift-off height, jet velocity, and nozzle diameter was derived and experimentally substantiated for its validity [1-2]. Also, the characteristics of the propagation speed of tri-brachial flame have been extensively analyzed theoretically and numerically in mixing layers considering such effects as heat generation [4-5], mixture fraction gradient [6], Lewis number [7-8], and buoyancy [9]. The major factors which having the influence on propagation speed have been identified as the mixture fraction gradient in front of a tri-brachial edge and the flow redirection effect resulting from heat generation along the curved premixed flame wings. Heat release is known to play an important role in the enhancement of the triple flame propagation speed as demonstrated by the numerical studies of Ruetsch [4]. The physical mechanism that contributes to the enhancement of the triple flame speed with heat release rate is directly associated with the streamline divergence ahead of the premixed branches followed by their subsequent convergence further downstream.

The stability analysis has been performed by assuming that the propagation speed is either constant or relatively insensitive to flow conditions [2]. The lifted flame is found to be stable/unstable when the local flow velocity along the stoichiometric contour decreases/increases with the axial distance in laminar free jets, which corresponds to the cases when Schmidt number, Sc of fuel is larger/smaller than unity [2]. Based on cold jet similarity solutions, experimentally it was shown that propane and n-butane fuels ($Sc > 1$) exhibited stable lifted flames, while no stable lifted flames were observed for methane and ethane fuels ($Sc < 1$) in free jets [1]. These lifted flames were stabilized in the far field of a jet when sub-millimeter size nozzles were used. Stationary lifted flames were also observed in highly diluted propane co-flow jet flames when relatively large size nozzle, O(10 mm), was used. Liftoff heights was increased with jet velocity and with fuel dilution. Based on the balance mechanism of a triple flame, jet velocity could be scaled with stoichiometric laminar burning velocity. There were two distinctive lifted flame stabilization modes were identified, in the developing and developed regions of co-flow jets [11]. It has been found that the buoyancy played an important role of flame stabilization. Also stationary lifted flames of methane diluted with nitrogen having ($Sc < 1$) were observed experimentally in the near field of co-flow jets [12]. To elucidate the stabilization mechanism for these flames, the behavior of the flame in the buoyancy free condition and unsteady propagation characteristics after ignition were investigated numerically. The flame stabilization under normal gravity was caused by the buoyancy. Decreasing trend in lift-off height with jet velocity was seen for methane/hydrogen lifted flames at low temperature 900 K than auto-ignition temperature [13], resulting in large lift-off height, at low jet velocity. It could indicate the importance of differential diffusion between methane and hydrogen in the jet mixing layer. But detailed computational work was not provided for such lifted flames.

Present study was made to elaborate the mechanism of nitrogen diluted methane lifted flames in the decreasing liftoff height regions. Such lifted flames are first investigated experimentally and will be discussed through numerical simulations. Which emphasizing that, stabilization mechanism of lifted flames in the decreasing liftoff height regions is due to the effect of buoyancy convection and radiative heat loss.

2 Experimental Set up and Numerical Simulation

The schematic diagram of experimental set up is as shown in the figure 1. It consisted of a co-flow burner, flow control system, visualization system. The burner had a central fuel nozzle with inner dimeters of 0.95 mm, 0.8 mm, 0.3 mm and its length were 100 times the inner diameter of the nozzle for the flow inside to be fully developed. The co-flow air was supplied to a coaxial nozzle with inner diameter of 92 mm through glass beads and ceramic honeycomb for the flow to be uniform. The quartz cylinder with 40 cm in length surrounded the co-flow air to minimize the outside disturbances and digital video camera (SONY, HDR-SR12) was placed for visualization. The fuel was chemically pure grade methane (>99%) diluted with nitrogen, was supplied to the central nozzle. The flow rates were controlled by mass flow controllers (ICDS Ltd.). Liftoff heights were measured by the cathetometer.

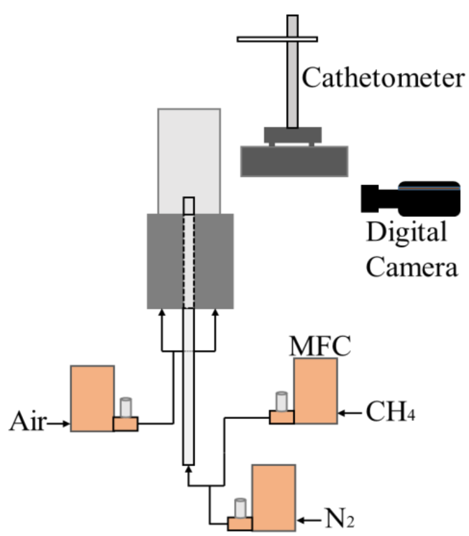

Figure 1. Schematic diagram of experimental set up

To simulate lifted flames in co-flow steady state axisymmetric cylindrical coordinate were solved for the momentum, species, and energy equations. Computations involving reduced kinetic mechanism were performed. Methane-air 2 step (3 reaction) overall reaction mechanism was adopted to account for the enthalpies of formation. Reactions are modeled using individual Arrhenius equations with forward reaction rate constant.

3 Results and Discussions

3.1 Flame stability and features in a laminar lifted co-flow jet flame

Experiments were conducted for methane diluted with nitrogen at various fuel mole fractions, $X_{F,O}$ and nozzles exit velocities, U_0 with nozzle of inner diameter, D = 0.95 mm. Co-flow velocity, V_{CO} was uniform as 7 cm/s. Figure 2, shows the flame stability map as function of U_0 and $X_{F,O}$. Two different types of regime of lifted flames were shown. In regime-I, H_L were decreased with increase in the U_0 at constant $X_{F,O}$ and regime-II corresponds to the increase in H_L with increase of U_0, at constant $X_{F,O}$. These lifted flames are observed for $Sc < 1$ as shown in figure 2. The phenomenon of increasing H_L with U_0 in free and co-flow jets has been explained previously in several studies [1-3, 11]. But behavior of decreasing H_L with U_0 at constant $X_{F,O}$ has never been discussed yet. Present study is mainly focused on these decreasing H_L regions in lifted flames.

Figure 3(a), shows the direct photographs of lifted methane jet flames diluted with nitrogen for $X_{F,O}$ = 0.27 with change in U_0. Lifted flame was exhibited at U_0 = 150 cm/s, with H_L = 6.38 mm, afterwards H_L was decreased with increased value of U_0, up to 250 cm/s. There was quenching distance within U_0 = 260 to 290 cm/s and flames were again lifted at U_0 = 300 cm/s with continuous increase in H_L with U_0. Initially at the ignition state for a specific $X_{F,O}$ and U_0, these methane jet flames attained a higher H_L prior to blow out. Such lifted flames exhibited tri-brachial flame structure and flame length increases appreciably with increase of U_0. Figure 3(b), shows the regions of decreasing and increasing H_L variation with U_0 and $X_{F,O}$. The range of decreasing H_L region was from $X_{F,O}$ = 0.26 to 0.32. At $X_{F,O}$ = 0.26, H_L were decreased with U_0 up to 260 cm/s and then without any quenching it keep lifted. In case of $X_{F,O}$ = 0.27 to 0.3, H_L of lifted flames were decreased with U_0, then attained a quenching distance. Later for some specific U_0 these flames were again lifted. But, for $X_{F,O}$ = 0.31 and 0.32 flames were attached to nozzle after decreasing H_L with U_0. The maximum liftoff height in the decreasing region were in the range of several millimeters to 9.86 mm. Our main concerns were fully focused on these decreasing liftoff height regions. In order to confirm decreasing tendency of liftoff height further experiments were performed using different nozzle inner diameters such as 0.3 mm, 0.8 mm. Co-flow velocity, V_{CO} = 7 cm/s was uniform throughout the experiment. Figure 4(a) and (b) shows the H_L variation with U_0 for nitrogen diluted methane jet flames at various $X_{F,O}$.

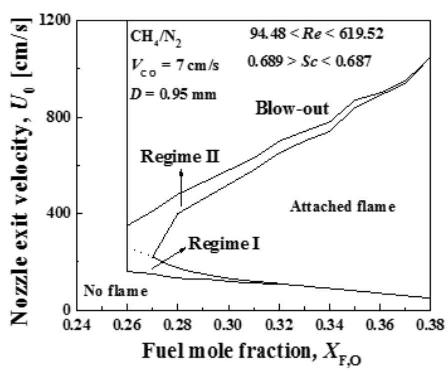

Figure 2. Flame stability map as a function of $X_{F,O}$ and U_0 for V_{CO} = 7 cm/s and D = 0.95 mm

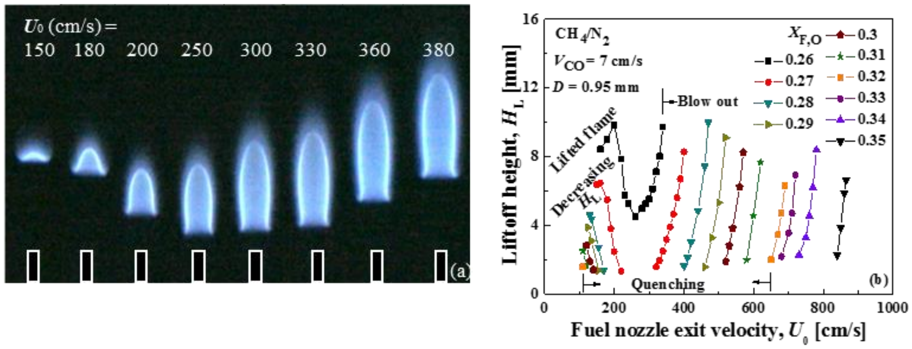

Figure 3. (a) Direct photographs of lifted methane jet flames diluted with nitrogen for $X_{F,O}$ = 0.27, at various U_0 (b) Liftoff height variations of lifted flame with U_0 for methane diluted with nitrogen at various $X_{F,O}$, for D = 0.95 mm.

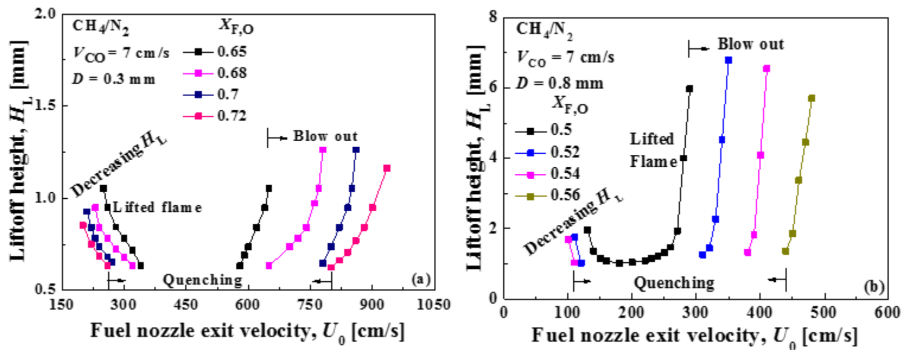

Figure 4. Liftoff height variations of lifted flame with U_0 for methane diluted with nitrogen (Sc < 1) at various $X_{F,O}$ for nozzle inner diameters of (a) 0.3 mm (b) 0.8 mm.

Similar investigations were observed for 0.3 and 0.8 mm nozzles as that of 0.95 mm nozzle, initially H_L were decreased with the increase of U_0 (at low U_0) for constant $X_{F,O}$. For D = 0.3 mm, H_L in the decreasing region are in the range of several millimeters to 1.05 mm whereas, in case of D = 0.8 mm they are within several millimeters to 1.96 mm. These lifted flames also maintained tri-brachial flame structure and flame size increased with decreasing H_L and increasing U_0. To elucidate the mechanism behind the decreasing H_L regions in lifted flames, further study is made.

3.2 Effect of buoyancy and radiation on lifted flames

In previous section, it was shown that H_L were decreased with increasing U_0 for methane jet flames diluted with nitrogen. Now, how these H_L were decreased with increasing U_0 has to be addressed. Note that, stabilization mechanism is still the balance of edge flame speed to the local flow velocity. This implies that, edge flame speed has to increase at low U_0. To clarify this, the behavior of lifted flame for the present diluted methane is tested numerically to elucidate the effect of buoyancy convection and radiative heat loss as they are correlated with heat release rate [8,10]. Figure 5, shows the evaluated heat release rate as a function of U_0 with stream line for coupled effect of buoyancy convection and radiative heat loss. Numerical simulations were conducted for nitrogen diluted methane jet flames at constant $X_{F,O}$ = 0.24 and with variation of U_0 for D = 0.95 mm. In this case, at U_0 = 0.4 m/s flame was lifted. It implies that, due to the effect of buoyancy convection and radiative heat loss and thereby heat release rate, streamlines are deflected towards the centerline and increase in the reactant fluxes to the edge flame, increasing the reaction rate of edge flame and hence edge flame speed. The amount of heat release rate was evaluated as,

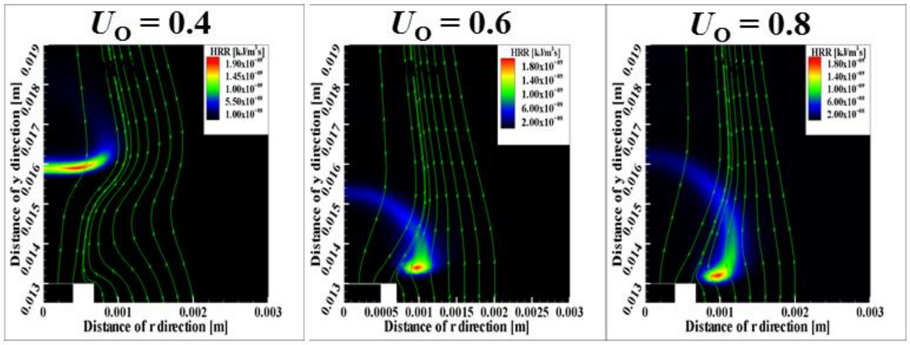

Figure 5. Effect of buoyancy convection and radiative heat loss as a heat release rate in nitrogen diluted methane lifted flames as function of U_0 and at constant $X_{F,O}$ = 0.24, in views of streamlines.

$$Q = \sum_{\alpha=1}^{N} \omega h_{f\alpha}^{0}$$

But for increasing U_0 = 0.6 and 0.8 m/s (at same $X_{F,O}$ = 0.24) streamlines diverge outward which indicates that, influence of buoyancy and radiation may suppress and H_L were decreased for them respectively. These results from numerical simulations were well matched with that of experimental results, H_L were decreased with increasing the U_0 at constant $X_{F,O}$ due to coupled effect of buoyancy convection and radiative heat loss and thereby heat release rate.

4 Conclusion

The stabilization mechanism of decreasing liftoff heights with increase in the nozzle exit velocities in lifted methane jet flames diluted with nitrogen (Sc < 1) were investigated experimentally and numerically. Characteristics of liftoff heights and flame stabilization in lifted flames were investigated with the effect of fuel nozzle exit velocity, fuel mole fraction, nozzle diameters. These decreasing liftoff height regimes were observed for various nozzle diameters 0.3 mm, 0.8 mm, and 0.95 mm. The present study, is focused on the lifted flame behaviors in decreasing liftoff height regime at low nozzle exit velocities. Results from numerical simulations identified that, buoyancy convection and radiative heat loss played a significant role in such decreasing behavior of liftoff heights with increase of nozzle exit velocity (particularly at low nozzle exit velocities).

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