Laminar Lifted Methane Jet Flames in Co-flow Air

Narayan P. Sapkal*, Won June Lee, Jeong Park*†, Byeong Jun Lee*†, Oh Boong Kwon

ABSTRACT

The Laminar lifted methane jet flames diluted with helium and nitrogen in co-flow air have been investigated experimentally. The chemiluminescence intensities of OH* and CH$_2$O* radicals and the radius of curvature for tri-brachial flame were measured using an intensified charge coupled device (ICCD) camera, monochromator and digital video camera. The product of OH* and CH$_2$O* is used as a excellent proxy of heat release rate. These methane jet flames could be lifted in buoyancy and jet dominated regimes despite the Schmidt number less than unity. Lifted flames were stabilized due to buoyancy induced convection in buoyancy-dominated regime. It was confirmed that increased OH* and CH$_2$O* concentration caused an increase of edge flame speed via enhanced chemical reaction in buoyancy dominated regime. In jet momentum dominated regime lifted flames were observed even for nozzle exit velocities much higher than stoichiometric laminar flame speed. An increase in radius of curvature in addition to the increased OH* and CH$_2$O* concentration stabilizes such lifted flames.

Key Words : Schmidt number, Richardson number, Buoyancy effect, Chemical effect, Edge flame speed

1. Introduction

Laminar lifted flames in non-premixed jets have been studied to clarify the characteristics of flame stabilization[1-3]. Such laminar lifted flames have tri-brachial flame structure: a lean premixed flame, a rich premixed flame and a trailing diffusion flame, all extending from a single location. Based on cold jet similarity solution, experimentally it was shown that propane and n-butane fuels ($Sc < 1$) exhibited stable lifted flame, while no stable lifted flame were observed for methane and ethane fuels ($Sc < 1$) in free jets [1]. Concurrently, for the lifted flame stabilization in hot co-flow environment, the important chemical role of intermediate species [6] such as, OH*, CH$_2$O* in laminar lifted flame stabilization has been investigated. Also it was perceived that product of OH* and CH$_2$O* can be used as a proxy for heat release rate [11]. Furthermore, the triple flame speed could be dependent upon many factors such as, mixture strength, heat loss, buoyancy, Lewis number[10]. In this regard, present study is to explore why laminar lifted methane jet flames diluted with helium and nitrogen ($Sc < 1$) can be stabilized. To confirm effect of buoyancy, Richardson number was evaluated and chemiluminescence intensities of OH* and CH$_2$O* and radius of curvature were measured.

2. Experimental set-up

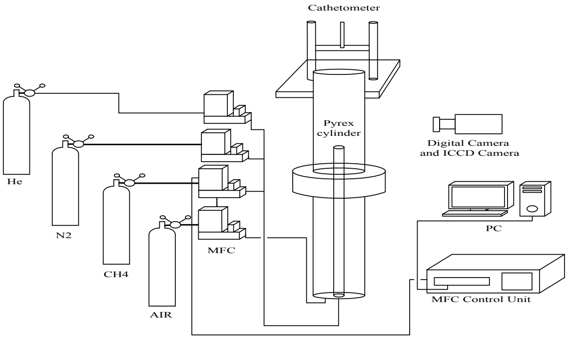

Fig. 1 Schematic diagram of experimental set-up

Experimental set-up consists of a co-flow b

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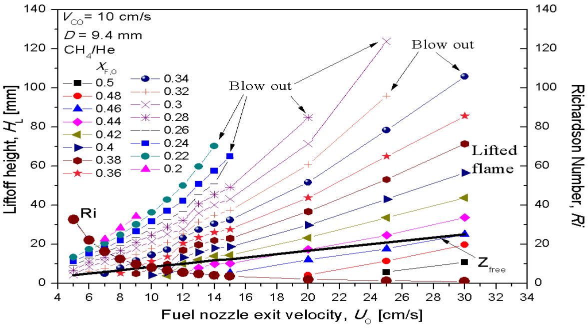
urner, a flow control system, visualization system. Two co-flow burners used had a central fuel nozzles with 9.4 and 0.95 mm inner diameters and length is 100 times of the inner diameter for the flow inside to be fully developed. The co-flow air was supplied to the co-axial nozzle with 90.4 mm i.d. passing through glass beads and aa honeycomb for the velocity to be uniform. The fuel was a pure grade methane diluted with helium and nitrogen and compressed air was used for the co-flow. The flow rates were controlled by mass flow controller. Digital video camera used to capture image of stationary lifted flame. Liftoff height was measured by the cathetometer. ICCD camera and monochromator were used to visualize the chemiluminescence and behaviors of lifted flame.

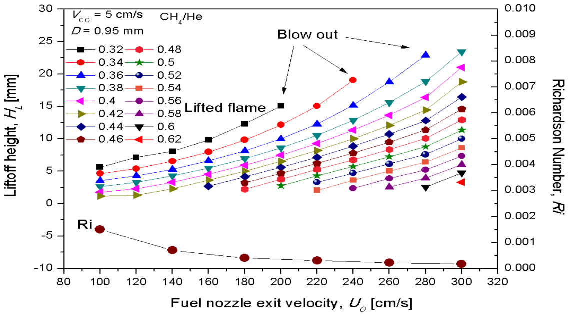
3. Results and Discussion

3.1 Stationary lifted flame

Experiments were conducted using 9.4 mm i.d. nozzle co-flow burner with co-flow jet velocity V_{CO} = 10 cm/s, by varying the fuel nozzle exit velocity U_O, and fuel mole fraction $X_{F,O}$ for methane jet flames diluted with helium is as shown in Fig. 2(a). Liftoff heights increased non-linearly with U_O and were in the range of several millimeters to 123.7 mm. For a reference, the developing region of a free jet, Z_{free} was marked by dotted line. This was obtained to be [8], Z_{free}/d= 0.0165 X Re_d. where Re_d is the Reynolds number defined as $U_o d./\nu$ and ν is the kinematic viscosity. The variation in Z_{free} with Uo is nearly linear which substantiates two different stabilization modes in the developing and developed regions of jet flame. Stabilizatio n mechanism has to be the balance



(a)



(b)

Fig. 2 Liftoff height variation with fuel nozzle exit velocity for methane diluted with helium (Sc < 1) at various fuel mole fraction for (a) 9.4 mm (b) 0.95 mm.

of edge flame speed to the local flow speed in respective of the stabilized location in the developed and developing regions. It was noted that, lifted flames are observed at smaller nozzle exit velocities less than stoichiometric unstretched laminar flame speed and this was depicted well by buoyancy effect. The effect of buoyancy was evaluated by Richardson number, $Ri = \Delta\rho g d/\rho Uo^2$, which was the ratio of buoyancy induced momentum to the jet momentum, where g was the gravitational acceleration, ρ was the unburned density and Δρ was the density difference between unburned and burned gases. Ri number for 5-30 cm/s is in the range of $0.8848 < Ri < 32.86$. The results shows that influence of buoyancy is more effective at low Uo with high Ri number and hence the stationary lifted flames were observed. But with an increase in the Uo the value of Ri number is decreasing precipitously and buoyancy effect is suppressed significantly. Also to obtain the lifted flames at much higher Uo than stoichiometric un-stretched laminar flame speed experiments were performed using 0.95 mm i.d. nozzle with Vco = 5 cm/s. variation of H_L with Uo in laminar lifted methane jet flames is shown in Fig. 2(b). Addition of helium diluent and increase in the Uo causes an increase in the H_L non-linearly until the flame is blown out. The triple flame structure was attained at high H_L. Ri number also evaluated to observe buoyancy effect and it was in the range of $0.0015 < Ri < 0.0017$. It is noted that, buoyancy effect can be suppressed and lifted flames were obtained at larger Uo than stoichiometric unstretched non-adiabatic flam

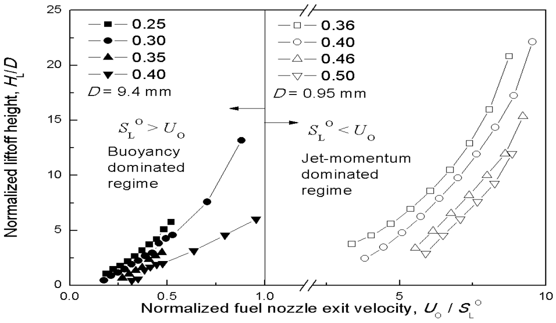


Fig. 3 Normalized liftoff height with fuel nozzle exit velocity considering stoichiometric un-stretched non-adiabatic laminar burning velocity for two different fuel nozzles.

e speed.

The lifted flames obtained from two different nozzle diameters co-flow burners are shown in Fig. 3. Using 9.4 mm diameter nozzle lifted flames are obtained at lower *U*o than S_L^o and with 0.95 mm i.d nozzle lifted flames are obtained at higher *U*o than S_L^o. This stoichiometric un-stretched non-adiabatic laminar burning velocity was achieved in a counter flow configuration through extrapolation of the linear relation of flame speed versus global strain rate.

Also, variation of H_L with *U*o for methane diluted with nitrogen at various $X_{f,o}$ is shown in Fig. 4. The flame edge has a triple flame structure even if it was not shown clearly. While nozzle attached flame edge shows the lean premixed flame wing is merged to the diffusion flame, such that the bi-brachial structure is exhibited. In this case, lifted flames were observed only in the developing region due to buoyancy effect at low *U*o and it was confirmed by evaluating *Ri* number. It was in the range of $0.15 < Ri < 32.11$. But at high *U*o, *Ri* number was decreased still lifted flames were observed. Further investigations may require to clarify the reason behind these lifted flames.

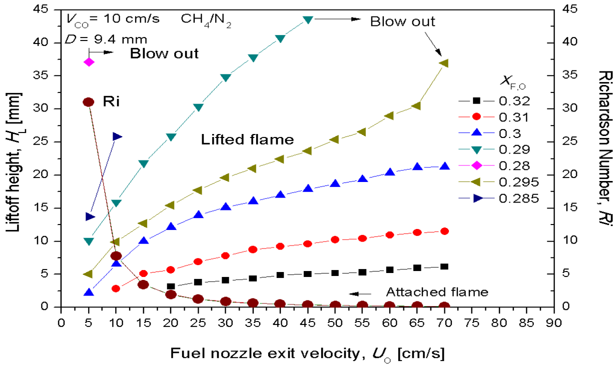
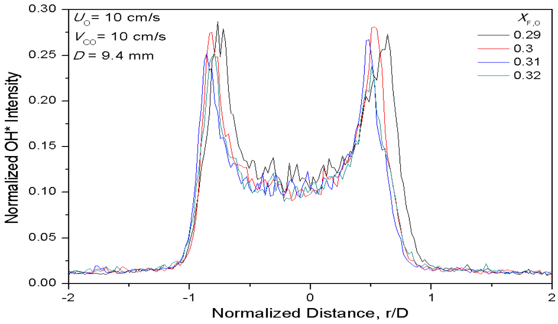


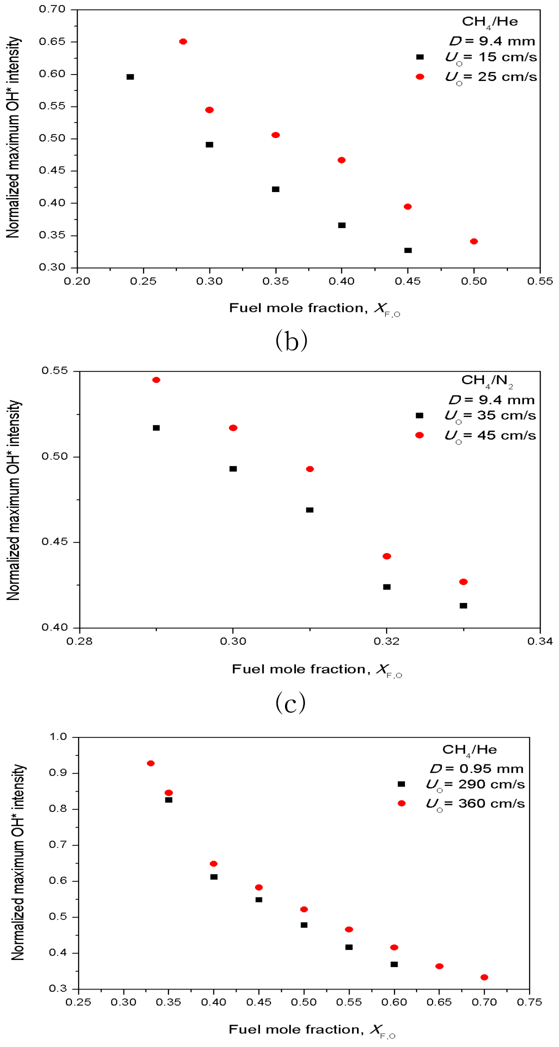
Fig. 4. Variation of H_L with U_O for methane diluted with Nitrogen ($Sc < 1$) at various $X_{F,O}$

3.2 Stabilization of lifted flames

In the previous discussions, lifted flames were observed for methane jet diluted with helium and nitrogen in buoyancy and jet momentum dominated regime. So how these lifted flames were stabilized is questionable. By stabilization mechanism, edge flame speed has to increase even with the mole fractions of helium and nitrogen despite the reduction in mixture strength. To clarify it, flame images were captured by the ICCD camera and chemiluminescence intensities of OH^* radicals are measured at various conditions. Typical radial distribution of chemiluminescence intensity is as shown in the Fig.5(a). The OH^* chemiluminescence intensities have maxima at the triple point, indicating a double peak. We investigated the normalized maximum OH^* intensity which was defined by the ratio of the OH^* intensity at triple point to the saturated intensity. Fig. 5 (b) and (c) shows that normalized maximum OH^* intensities decreased with increasing fuel mole fraction and increased with helium and nitrogen mole fraction for *D* = 9.4 mm nozzle diameter, which corresponds to buoyancy dominated regime. This implies that, buoyancy induced convection increases the reactant fluxes to the edge flame, increasing the reaction rate of edge flame and hence edge flame speed. Similar investigations were observed *D* = 0.95 mm nozzle diameter as shown in Fig. 5(d). Normalized maximum OH^* intensity increases with helium mole fraction as well. For such a high *U*o, Richardson number and hence buoyancy effect is negligible, meaning that there are some other reasons.



(a)



(b)

(c)

(d)

Fig. 5 (a) Typical Radial distribution of chemiluminescence intensity passing through the triple point at various $X_{F,O}$. Measured OH* radical intensities for (b) methane diluted with helium at U_o = 15 and 25 cm/s (c) methane diluted with nitrogen at U_o = 35 and 45 cm/s, using 9.4 mm nozzle diameter (d) methane diluted with helium at U_o = 290 and 360 cm/s using 0.95 mm nozzle inner diameter.

Also, the product of OH^* and CH_2O^* is obtained using monochromatic experiment as shown in Fig. 6, which is the marker for heat release rate as per previous studies [11]. It implies that, increase in the reaction rate and hence edge flame speed. It is to be noted that, edge flame speed is dependent upon mixture strength, buoyancy, fuel concentration gradient and thereby radius of curvature. Hence important role on edge flame speed enhancement may addressed to the radius of curvature. Fig. 7, shows the appreciable increase in the radius of curvature and thereby increasing edge flame speed.

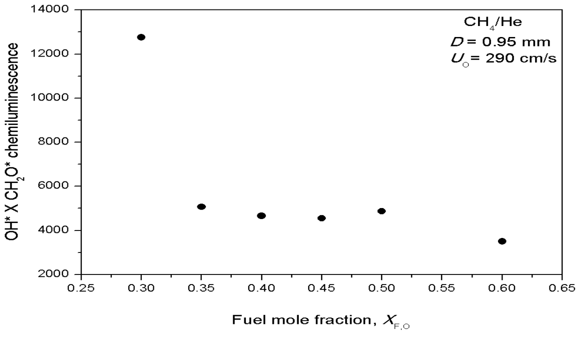


Fig. 6. Product of OH^* and CH_2O^* as marker for heat release rate.

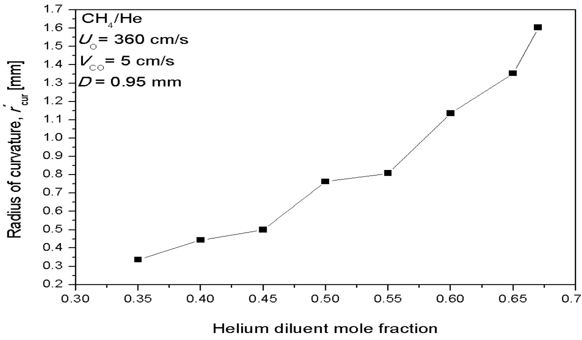


Fig. 7 Radius of curvature r^*_{cur}, of lifted methane jet flame with helium dilution.

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