Experimental Study on Laminar Lifted Methane Jet Flame Diluted with Nitrogen and Helium

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Abstract

Laminar lifted co-flow methane jet flames diluted with nitrogen and helium have been investigated experimentally. The OH* chemiluminescence intensities, which could be a good indicator of heat release rate, and the radii of curvature for tri-brachial flame were also measured using an intensified charge-coupled device (ICCD) camera and digital camera at various conditions. Such jet flames with 0.95 and 9.4 mm nozzle diameters could be lifted despite the Schmidt number less than unity in both buoyancy-dominated and jet-momentum-dominated regimes. The methane jet flames diluted with nitrogen and helium could be also lifted even at nozzle exit velocities much higher than stoichiometric laminar flame speeds. In such buoyancy-dominated regime, lifted flame was stabilized due to buoyancy-induced convection, causing increase of reactant mass flux to edge flame, thereby increasing the reaction rate and subsequently edge flame speed. It was confirmed by increased OH* concentration (thereby increase of edge flame speed via enhanced chemical reaction). In jet-momentum-dominated regime, appreciable increase of radius of curvature stabilizes such lifted flames. Detailed discussion on the stabilization of such lifted flames is made based on the stabilization mechanism.

Introduction

Lifted flames in non-premixed jet configurations have been studied extensively to grasp the fundamental characteristics of flame stabilization and safety in industrial burners. In particular, laminar lifted non-premixed jet flames has been widely studied as well [1-3], in that those can provide an excellent target field for development of advanced laminar stretched flame let model via permitting partially premixed mixture. Such a laminar lifted flame propagates along the stoichiometric contour due to the intrinsic nature at its base such that the leading edge consists of a lean and rich premixed flame wings and a trailing diffusion flame. Thus, the stabilization mechanism is addressed to the balance between the propagation speed of tri-brachial flame and local axial flow velocity. Based on cold jet similarity solution, it was shown experimentally that propane and n-butane fuels (*Sc* > 1) exhibited stable lifted flames, while no stable lifted flame was observed for methane and ethane fuels (*Sc* < 1) in free jets [1].

However, the stabilization mechanism of lifted flame edge in the near field of co-flow jets for diluted methane and stationary lifted flame has been investigated experimentally [4]. Stationary lifted flames were also observed in co-flow jets for propane highly diluted with nitrogen when relatively large size nozzles with the diameter *d*= O (10mm) were used [5]. Based on the balance mechanism of a tri-brachial flame, jet velocity could be scaled with stoichiometric laminar burning velocity. Results show two distinctive lifted flame stabilization modes in the developing and developed regions of jets depending on the initial fuel mole fraction. Meanwhile, for the lifted flame stabilization in hot co-flow environments [6], important chemical role of intermediate species such as, OH*, CH_2O (which increased with strain) in laminar lifted flame stabilization (through reduction in ignition delay time) has been investigated. Also it was recognized that OH* are a good indicator of heat release rate [7]. In a propagating tri-brachial flame, correlation of edge flame speed to fuel concentration gradient was addressed using the dependency of fuel concentration gradient upon radius of curvature [3]. Relevance of flow redirection to heat release was explained in detail [10]. Additionally, the tri-brachial flame speed could be sensitively dependent upon many factors such as mixture strength, buoyancy, heat loss, and Lewis number [11]. Motivated by this, the present study is to explore why laminar lifted methane jet flame diluted with nitrogen and helium (*Sc* < 1) can be stabilized. Richardson number *Ri*, is evaluated to check the effect of buoyancy and chemiluminescence intensities of OH* have been measured by an intensified charge-coupled device (ICCD) camera at various conditions. Also the radius of curvature, which is one of the main mechanism of the stabilization of triple flame, is measured at various conditions as well.

Experimental set-up

The experimental apparatus consisted of a co-flow burner, a flow control system, and a visualization set up, as schematically shown in Fig.1. Two co-flow burners used had a central fuel nozzle made of stainless steel with

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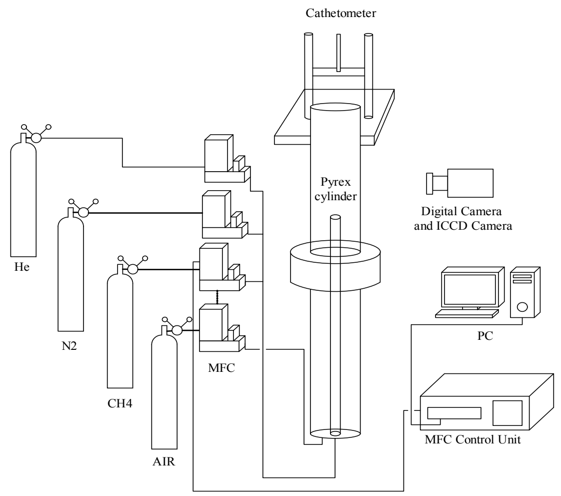


Fig. 1 Schematic diagram of experimental setup.

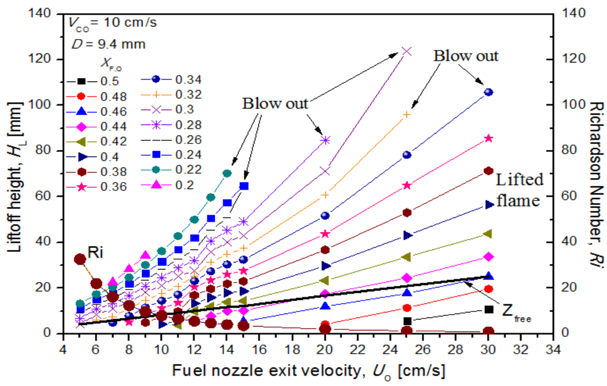
9.4 mm and 0.95 mm inner diameters, and the length is 100 times of the inner diameter for the flow inside to be fully developed. The co-flow air was supplied to the coaxial nozzle with 90.4 mm inner diameter through a glass beads and honeycomb for the velocity to be uniform. The tip of the fuel nozzle protruded 10.3 mm over the honeycomb. A Pyrex cylinder with 40 cm length and 90.4 mm inner diameter was placed on the honeycomb, to minimize outside disturbances. The fuel was a pure grade of methane diluted with nitrogen and helium, compressed air was used for the co-flow. The flow rates were controlled by mass flow controllers. The visualization setup consisted of a digital video camera (SONY, HDR- CX560) which was triggered to capture the image of stationary lifted flame and an intensified charge-coupled device (ICCD) camera (Princeton Instruments, Inc. PI-MAX4:2048f) was used to visualize the flame. The lift off height was measured by a cathetometer.

Results and discussion

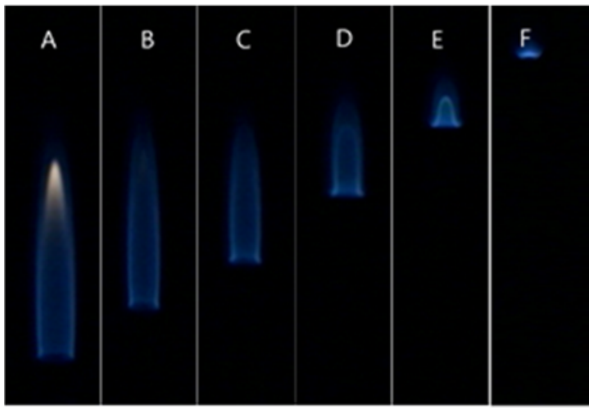
Stationary lifted flames

Experiments were performed for 9.4 mm i.d. nozzle co-flow burner by varying the fuel nozzle exit velocity, U_O and initial fuel mole fraction, $X_{F,O}$. Outer co-flow jet velocity, V_{CO}, was fixed at 10 cm/s. Variation of liftoff height with jet velocity is plotted in Fig. 2(a) for methane diluted with helium at various $X_{F,O}$. Overall, the liftoff height increased nonlinearly with U_O. The liftoff heights were in the range of several millimeters to 123.7 mm. Fig. 2(b) shows the direct photographs of lifted flame at U_O = 14 cm/s for various fuel mole fractions. At $U_{O,}$ 5 to 9 cm/s, lower than fixed co-flow velocity, such flames were reattached to the nozzle. By addition of helium diluent liftoff height increased with U_O until blowout occurred and for $0.2 < X_{F,O} < 0.34$, the flame was blown out when the flame base became nearly flat. Stationary lifted flames were observed in the co-flow jets for methane diluted with helium despite $Sc < 1$.

There were two different stabilization modes for the diluted propane [5] in the developing and developed reg-



(a)



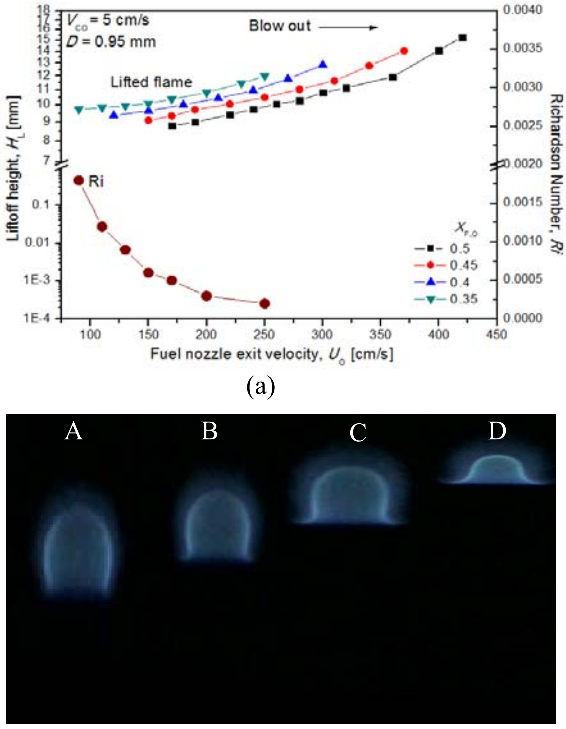
(b)

Fig. 2 (a) Variation of liftoff height of stationary lifted flames with fuel nozzle exit velocity for methane diluted with helium ($Sc < 1$) at various fuel mole fractions, and (b) direct photographs of stationary lifted methane jet flame diluted with helium for U_O = 14 cm/s, at (A) $X_{F,O}$ = 0.45 (B) 0.4 (C) 0.35 (D) 0.3 (E) 0.25 (F) 0.22.

ions of the co-flow jets. As a reference, the length of the developing region of a free jet, Z_{free}, by neglecting co-flow jet is marked by a dotted line. This is estimated to be Z_{free}/d =0.0165 X Re_d [9], where Re_d is the Reynolds number defined as, $U_O d/\nu$ and ν is the kinematic viscosity. Since the fuel is diluted, the ν for helium is adopted for simplicity. The results shows that for $X_{F,O} > 0.46$, the liftoff height is even smaller than Z_{free}. The variation of Z_{free} with U_O is nearly linear and is plotted in Fig. 2(a), which further substantiates two different stabilization modes in the developed and developing regions of jets. These two different stabilization modes of lifted flames existed depending on whether the stabilization location was in the developed region (for small $X_{F,O}$ and large H_L) or in the developing region (for relatively large $X_{F,O}$ and small H_L) of co-flow jets. Despite the existence of lifted flame in the developed and developing regions, the stabilization mechanism has to be the balance of edge flame speed to the local flow speed. Note that the flames are lifted at smaller nozzle exit velocities less than stoichiometric un-stretched laminar flame speeds. This was well explained by buoyancy effects [4]. Based on this, the effect of buoyancy was evaluated by the Richardson number as, $Ri = \Delta\rho g d$ /

ρU^2_O, which was the ratio of the 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. In the Fig. 2(a) the *Ri* number evaluated for U_O = 5-30 cm/s at different stoichiometric conditions from 0.2 < $X_{F,O}$ < 0.5 is in the range of 0.8848 < *Ri* < 32.86. The results suggest that, at low U_O, (5-9 cm/s) with high *Ri* number, buoyancy effect is more influential and hence the stationary lifted flame is formed. But with increase in the U_O, from (10-30 cm/s) the value of *Ri* number is decreases and buoyancy is suppressed significantly. It was seen that in the developing region lifted flames are formed due to the influence of buoyancy (at low U_O) but with increase in the U_O, buoyancy effect is minimal.

Also to obtain the lifted flame at much higher U_O than stoichiometric un-stretched laminar flame speed, experiment were conducted using 0.95 mm i.d. nozzle co-flow burner by varying the U_O and $X_{F,O}$. Co-flow velocity, V_{CO}, was fixed to 5 cm/s as well. Fig. 3(a) shows variation of liftoff height H_L with U_O for methane diluted with helium at various $X_{F,O}$. Liftoff height increases non-linearly. With the addition of helium diluent and with increasing U_O, H_L increases until the flame is blown out. The range of H_L is between 7 mm to 15 mm. Fig 3(b) shows the direct photographs of the lifted flame for $X_{F,O}$ = 0.45 at various U_O. At high H_L, tri-brachial flame structures were attained. To observe the buoyancy effect, Richardson number was also evaluated as discussed before, which is in the range of 0.0002 < *Ri* < 0.0018. So it is considered that, in this case, buoyancy effect can be suppressed. Note that such lifted flames were obtained for U_O, larger than stoichiometric un-stretched laminar burning velocities. Fig. 4 shows the lifted flames obtained from two different nozzle diameter co-flow burners. By using 9.4 mm diameter nozzle co-flow burner, lifted flames are obtained at lower U_O than S_L^0 and for 0.95 mm diameter nozzle lifted flames are obtained at higher U_O than S_L^0. The stoichiometric un-stretched non-adiabatic laminar burning velocities were evaluated by using the oppdif code GRI mechanism. This was because the evaluation with adiabatic flame via Premixed code could not describe the effect of helium addition with high thermal conductivity. Un-stretched non-adiabatic stoichiometric laminar flame speeds was achieved via extrapolation of the linear relation of flame speed versus global strain rate in a counterflow configuration. From Fig. 4, it is confirmed that lifted flame existed for methane diluted with helium even at high U_O than non-adiabatic stoichiometric un-stretched laminar burning velocities. In such cases, this implies that some another factors can be addressed to flame stabilization which will be discussed later.



(a)

(b)

Fig. 3 (a) Liftoff height variation with nozzle exit velocity for methane diluted with helium at various $X_{F,O}$ and (b) direct photographs of lifted methane jet flame diluted with helium for $X_{F,O}$ = 0.45, at (A) U_O = 150 (B) 220 (C) 310 (D) 370 cm/s

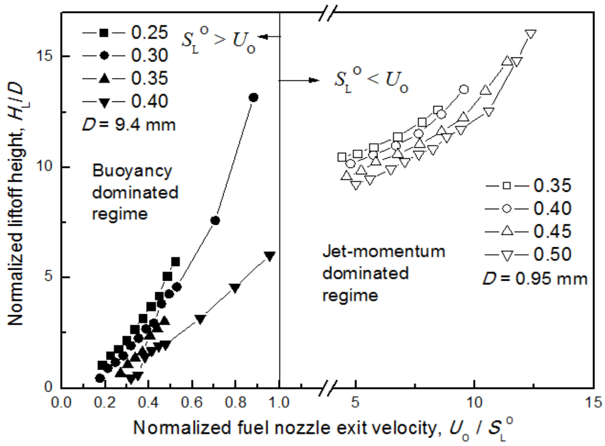
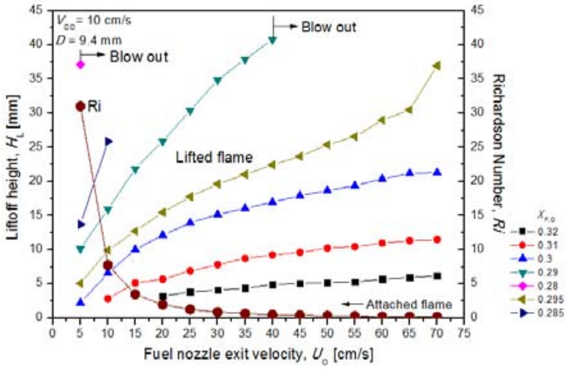
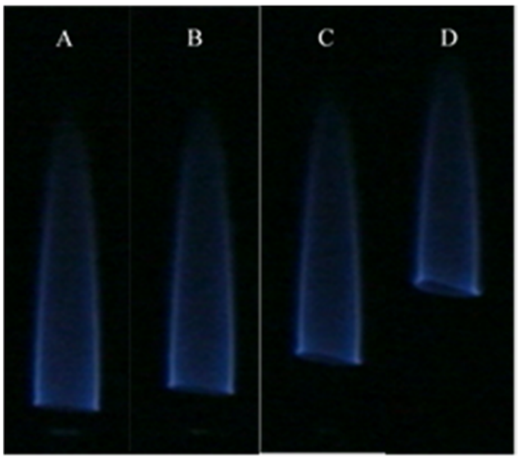


Fig. 4 Normalized liftoff height with fuel nozzle exit velocity considering stoichiometric un-stretched non-adiabatic laminar burning velocity for two different fuel nozzles.

Fig. 5(a) shows the liftoff height variation with nozzle exit velocity at various $X_{F,O}$ for methane diluted with nitrogen. Fig. 5(b) shows the direct photographs of stationary lifted flame for U_O = 20 cm/s at various $X_{F,O}$. Although not shown clearly, the flame edge has a tri-brachial structure, even though the lean premixed flame wing is somewhat obscure. This is because the edge is located near the nozzle where the mixture fraction gradient is expected to be large. The flame edge structure demonstrates the tri-brachial nature when H_L is large, while the nozzle attached flame edge shows that the lean premixed flame wing is merged to the diffusion flame, such that the bi-brachial structure is exhibited. Note that the flame length increases appreciably with U_O.



(a)



(b)

Fig. 5 (a) Variation of liftoff height with nozzle exit velocity for methane diluted with nitrogen (*Sc* < *1*) at various fuel mole fractions, and (b) direct photographs of stationary lifted methane jet flame diluted with nitrogen for U_O = 20 cm/s at (A) $X_{F,O}$ = 0.32 (B) 0.31 (C) 0.3 (D) 0.29.

Flame flickering occurs near the tip region for U_O > 20 cm/s. Even with flickering, its influence on the liftoff height was negligible. The mechanism of flickering for non-premixed flames due to the Kelvin-Helmholtz instability [8] has been previously investigated. The blowout is observed at U_O = 40 cm/s for $X_{F,O}$ = 0.29. Stationary lifted flames were observed in the near field of co-flow jets for methane diluted with nitrogen (*Sc* < 1). As discussed before, there were two different stabilization modes for the diluted propane [5] in the developing and developed regions of the co-flow jets. But for the methane diluted with nitrogen, stationary lifted flames are observed only in the developing region until blowout occurs. This is consistent with the previous findings in the free jets that a lifted flame for methane having *Sc* < *1* is unstable and cannot be stabilized as stationary lifted flame in the developed region [1-2]. These lifted flames in the developing region are considered due to the influence of buoyancy at low U_O and this was checked by considering Richardson number *Ri* [4]. In the Fig. 3(a) *Ri* number calculated for U_O = 5-70 cm/s at various stoichiometric conditions 0.29 < $X_{F,O}$ < 0.32 are in the range of 0.15 < *Ri* < 32.11. This results shows that, at low U_O, (5-20 cm/s) buoyancy effect is more influential where *Ri* number is very large. Also buoyancy effect was elucidated numerically for diluted methane by considering the reaction rate contours and streamlines in buoyancy and buoyancy free condition [4]. It was demonstrated that, the stationary lifted flame, stabilized due to buoyancy effects, was converted to the nozzle attached flame in microgravity. Furthermore, even if Richardson number and hence buoyancy effect also decreased with the increased $U_{O,}$ from (25-70 cm/s), stationary lifted flame are formed still in this region. In this regard, further investigation may be required to clarify them.

Stabilization of lifted flame

In previous section, it was shown that lifted flame for methane jet diluted with helium and nitrogen existed in buoyancy-dominated and jet-momentum-dominated regimes. Now, how lifted flames were stabilized in buoyancy-dominated and jet-momentum-dominated regimes has to be addressed. Note that the stabilization mechanism is still the balance of edge flame speed to the local flow one. This implies that edge flame speed has to increase even with mole fractions of helium and nitrogen despite reduction of mixture strength. To confirm it, flame images were first captured by the intensified charge-coupled device (ICCD) camera and chemiluminescence intensities of OH* radicals (an indicator of heat release rate [7] are measured at various flame conditions. Fig. 6 shows typical radial distributions of OH* chemiluminescence intensity passing through the triple point at various $X_{F,O}$ for U_O = 27 cm/s and V_{CO} = 10 cm/s in case of D = 9.4 mm. In Fig. 6, the OH* chemiluminescence intensities have maxima at the triple points, indicating a double peak. Based on them, maximum OH* chemiluminescence intensities were examined at various $X_{F,O}$ and U_O .

Fig. 7 shows measured OH* radical intensities for (a) methane diluted with helium at U_O = 30 cm/s (b) methane diluted with nitrogen at U_O = 27 cm/s, for various $X_{F,O}$ using 9.4 mm diameter nozzle, and thereby corresponding to buoyancy-dominated regime in Fig. 4. In this case, increasing mole fractions of helium and nitrogen increases maximum OH* intensities. This implies that buoyancy-induced convection increases the reactant fluxes to the edge flame, increasing the reaction rate of edge flame and thereby edge flame speed. The same investigation was made at U_O = 200 cm/s for D = 0.95 mm, and shown in Fig. 8. The maximum OH* intensity also increases with helium mole fraction. Note that the Richardson number is negligible for such a high nozzle exit velocity (thereby identified to jet-momentum dominated regime). Then, such a tendency may not be explained by the effect of buoyancy but the other reason. Even if we do not provide them, OH* concentration decreases with diluents mole fraction of He and N_2 at a fixed strain rate in a counterflow configuration. Then, the feasibility of enhanced edge flame speed via chemical effects may be excluded. Nonetheless, the feasibility in

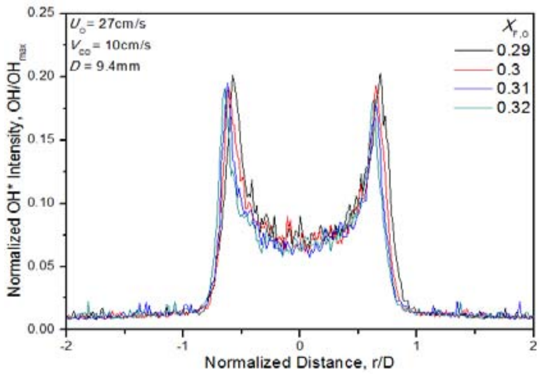
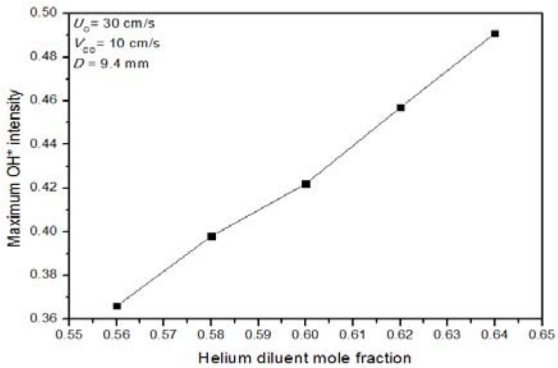
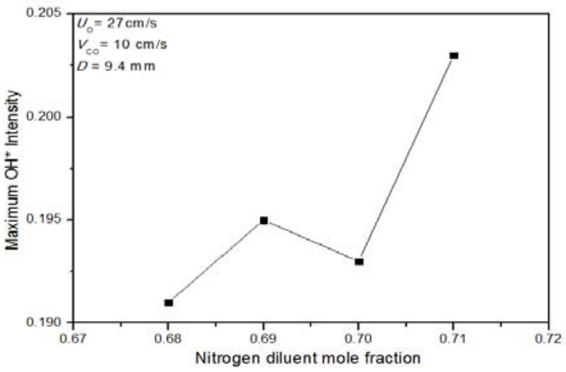


Fig. 6 Typical radial distributions of chemiluminescence intensity passing through the triple point at various $X_{F,O}$ for U_O = 27 cm/s and V_{CO} = 10 cm/s in case of D = 9.4 mm.



(a)



(b)

Fig. 7 Measured OH* radical intensities for (a) methane diluted with helium at U_O = 30 cm/s and (b) methane diluted with nitrogen at U_O = 27 cm/s, for various $X_{F,O}$ using 9.4 mm nozzle diameter .

high temperature ambience will remain in future works because the stabilization mechanism has a jump from the balance of edge flame speed to the local speed one at normal temperature ambience to reduction in ignition delay time at high temperature ambience.

Note that edge flame speed is dependent upon mixture strength, buoyancy, fuel concentration gradient (strain rate and thereby radius of curvature), and Lewis number. Because diluents addition decreases mixture strength, it has a negative effect in flame stabilization. In

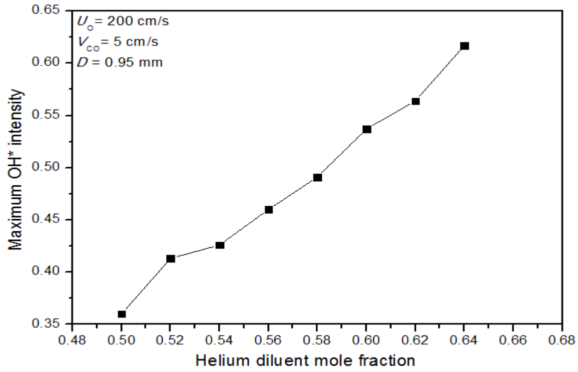
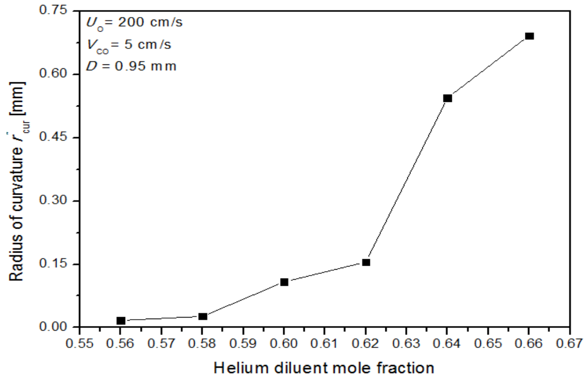


Fig. 8 Measured OH* radical intensities for methane diluted with helium at U_O = 200 cm/s and various $X_{F,O}$ using 0.95 mm nozzle diameter.



(b)

Fig. 9 Radius of curvature r^*_{cur}, of lifted methane jet flame with the addition of helium dilution by using 0.95 mm nozzle diameter.

a jet-momentum dominated regime, buoyancy effects are also negligible as shown in Fig. 4. Lewis number was in he range of 1.08~1.36 (0.963~0.964) for helium (nitrogen) addition (both decrease with fuel mole fraction), respectively. Particularly, for helium addition, it has a negative effect in edge flame speed such that the Lewis number increases with helium mole fraction. This implies that the effect of Lewis number cannot be a main reason of flame stabilization. Thus important role on edge flame speed enhancement may be addressed to radius of curvature. Fig. 9 shows variations of radius of curvature with He mole fraction in jet-momentum-dominated regime (with D = 0.95 mm). Radius of curvature increases appreciably with He mole fraction in jet-momentum-dominated regime, thereby increasing edge flame speed. Consequently, for lifted methane jet flame diluted with helium, radius of curvature was increased with the addition of helium diluent which causes the increase in edge flame speed which could be balanced with the local flow one. For further confirmation, experiments are still being conducted.

Conclusion

The stabilization mechanism of lifted methane jet flame diluted with nitrogen and helium ($Sc < 1$) has been investigated experimentally. Lifted flames were observed for methane diluted with helium in both developing and developed regions. For 9.4 mm nozzle diameter, lifted flames existed at $U_O < S_L^O$. Based on the flame stabilization mechanism, the stabilization of lifted flames were caused by buoyancy-induced convection flow such that it could increase reactant mass fluxes to edge flame (increasing the reaction rate and edge flame speed). However, even in jet-momentum-dominated regime (experimented with D = 0.95 mm nozzle diameter), lifted flame diluted with helium existed. It was found that, in such lifted flames, appreciable increase of radius of curvature contributed to the stabilization.

Acknowledgements

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References

[1] S.H. Chung, B.J. Lee, On the characteristics of laminar lifted flames in a non-premixed jet. Combust. Flame 86 (1991) 62-72.

[2] B.J. Lee, S.H. Chung, Stabilization of lifted tri-brachial flames in a laminar non-premixed jet. Combust. Flame 109 (1997) 163-172.

[3] Y.S. Ko, S.H. Chung, Propagation of unsteady tri-brachial flames in laminar non-premixed jets. Combust. Flame 118 (1999), 151-163.

[4] S.H. Won, J. Kim, K.J. Hong, M.S. Cha, S.H. Chung, Stabilization mechanism of lifted flame edge in the near field of co-flow jets for diluted methane. Proc. Combust. Inst. 30 (2005) 339-347.

[5] S. H. Won, S. H. Chung, M. S. Cha and B. J. Lee, Lifted flame stabilization in developing and developed regions of co-flow jets for highly diluted propane. Proc. Combust. Inst. 28 (2000) 2093-2099.

[6] Paul R. Medwell, David L. Blunck, Bassam B. Dally, The role of precursors on the stabilization of jet flames issuing into a hot environment. Combust. Flame 161 (2014) 465-474.

[7] Y. Hardalupas, M. Orain, Local measurements of the time-dependent heat release rate and equivalence ratio using chemiluminescent emission from a flame. Combust. Flame 139 (2004) 188-207.

[8] J. Buckmaster, N. Peters, The infinite candle and its stability: A paradigm for flickering diffusion flames, Proc. Combust. Inst. 21 (1986) 1829-1836.

[9] Lee, D.S., S.H. Chung and K.D. Kim, J. Fluid Engin. Trans. ASME, 119: 716-718, (1997).

[10] Ruetsch, G.R., Vervisch, L., and Linan, A., Phys. Fluids 7:1447-1454 (1995).

[11] S.H. Chung, Stabilization, propagation and instability of tri-brachial triple flames, Proc. Combust. Inst.31 (2007) 877-892.