J. Korean Soc. Combust. 20(3) (2015) 1-7

〈학술논문〉 http://dx.doi.org/10.15231/jksc.2015.20.3.001 ISSN 1226-0959

A Study on Laminar Lifted Jet Flames for Diluted Methane in Co-flow Air

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(Received 13 May 2015, Received in revised form 20 June 2015, Accepted 22 June 2015)

ABSTRACT

The laminar lifted jet flames for methane diluted with helium and nitrogen in co-flow air have been investigated experimentally. Such jet flames could be lifted in both buoyancy-dominated and jet momentum dominated regimes (even at nozzle exit velocities much higher than stoichiometric laminar flame speed) despite the Schmidt number less than unity. Chemiluminescence intensities of OH* radical (good indicators of heat release rate) and the radius of curvature for tri-brachial flame were measured using an intensified charge coupled device (ICCD) camera and digital video camera at various conditions. It was shown that, an increase in OH* concentration causes increase of edge flame speed via enhanced chemical reaction in buoyancy dominated regime. In jet momentum dominated regime, an increase in radius of curvature in addition to the increased OH* concentration stabilizes such lifted flames. Stabilization of such lifted flames is discussed based on the stabilization mechanism.

Key Words : Lifted flames, Buoyancy effect, Schmidt number, Richardson number, Chemiluminescence, Radius of curvature

기호설명

D	: Fuel nozzle diameter	ρ	: Gas density
Uo	: Fuel nozzle exit velocity	g	: Gravitational acceleration
Vco	: Coflow-air velocity	H_L	: Liftoff height
S_L^o	: Un-stretched non-adiabatic stoichiometric laminar burning velocity	Sc	: Schmidt number
		Re	: Reynolds number
$X_{F,O}$	: Initial fuel mole fraction	Ri	: Richardson number
r_{cur}	: Radius of curvature	Le	: Lewis number

1. Introduction

Laminar lifted non-premixed jet flames have been widely studied[1-3], to grasp the fundamental characteristic of flame stabilization. The leading edge of such lifted flames consists of a lean and rich premixed flame wings and a trailing diffusion flame and referred as tri-brachial flames. 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, experimentally it was shown that propane and n-butane fuels ($Sc > 1$) exhibited a stable lifted flames, while no stable lifted flames were observed for methane and ethane fuels ($Sc < 1$) in free jets[1]. Also, stationary lifted flames were observed for propane highly diluted with nitrogen in co-flow jets when relatively large size nozzle with the diameter $d = O$ (10 mm) were used[5]. In that, results show two distinctive lifted flame stabilization modes in the developing and developed regions of jets depending on the initial fuel mole fraction.

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Meanwhile, for the lifted flame stabilization important role of intermediate species such as OH^*, CH_2O in laminar lifted flame stabilization has been investigated in hot co-flow environments[6]. Also it was recognized that OH* are the good indicators of heat release rate[7]. For a propagating triple flame, dependency of fuel concentration gradient upon radius of curvature addresses the correlation of edge flame speed to fuel concentration gradient[3]. The concernment of flow redirection with heat release rate was also explained in detail[10]. Additionally, the tri-brachial flame speed could be sensitively dependent upon many other factors such as, mixture strength, heat loss, buoyancy, and Lewis number[11]. Motivated by this, the present study is to explore why the laminar lifted methane jet flames diluted with helium and nitrogen having ($Sc < 1$) 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 radii of curvature, which is one of the main mechanism of the stabilization of tri-brachial flame, is measured at various conditions.

2. Experimental set-up

Experimental setup consists of a co-flow burner, a flow control system, and a visualization system as shown in the Fig. 1. Two co-flow burners used had a central fuel nozzles with 9.4 mm and 0.95 mm inner diameters made of stainless steel and the length is 100 times of the inner diameter for the flow inside to be fully developed. A pyrex cylinder with 40 cm in length and 90.4 mm inner diameter was placed on the honeycomb, to minimize the outside disturbances. 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 fuel was a pure grade of methane diluted with the helium and nitrogen, and the compressed air was used for the co-flow. The flow rates were controlled by the mass flow controllers. The visualization system consists 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 behavior of lifted flame. The liftoff height was measured by the cathetometer.

3. Results and discussion

3.1. Stationary lifted flames

The change in liftoff height H_L, with fuel nozzle exit velocity *U*o, for 9.4 mm i.d. nozzle co-flow burner is shown in the Fig. 2(a). Co-flow velocity *V*co, was fixed

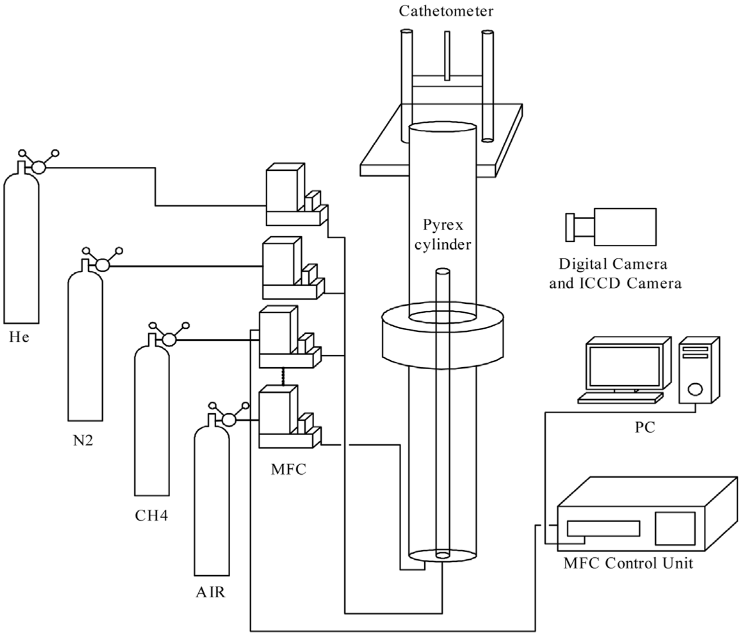

Fig. 1. Schematic experimental setup and flow system about co-flow jet burner.

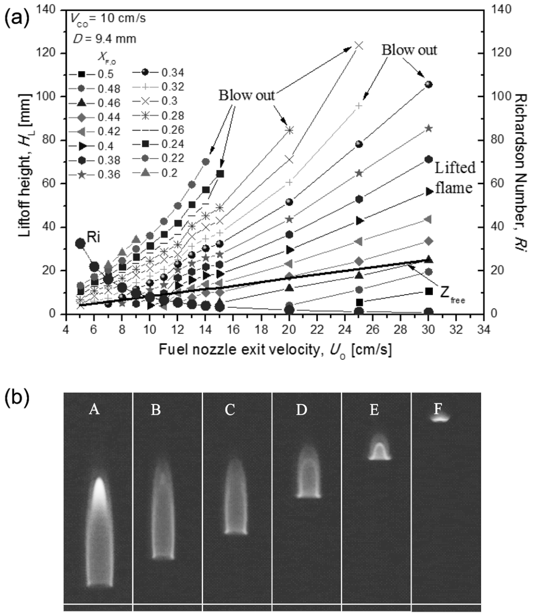

Fig. 2. (a) Change in liftoff height with fuel nozzle exit velocity for methane diluted with helium (*Sc* < 1) at various $X_{F,O}$ (b) direct photographs of stationary lifted methane jet flame diluted with helium for *U*o = 14 cm/s, at (A) $X_{F,O} = 0.45$ (B) 0.4 (C) 0.35 (D) 0.3 (E) 0.25 (F) 0.22.

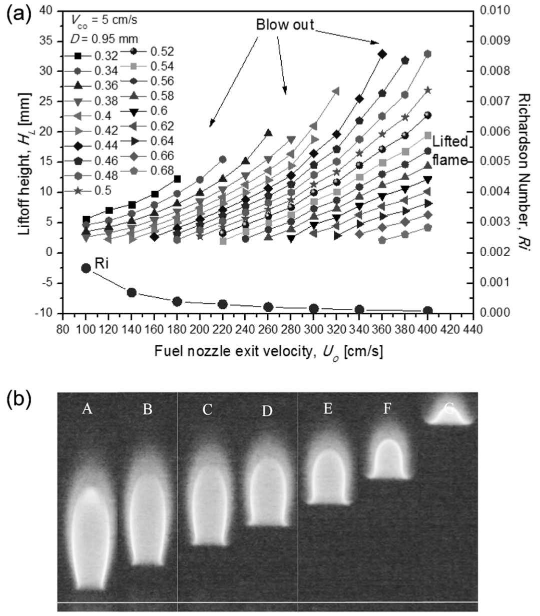

Fig. 3. (a) Change in liftoff height with fuel nozzle exit velocity for methane diluted with helium (*Sc* < 1) at various $X_{F,O}$ and (b) direct photographs of lifted methane jet flame diluted with helium for *U*o = 260 cm/s, at (A) $X_{F,O} = 0.6$ (B) 0.56 (C) 0.52 (D) 0.48 (E) 0.44 (F) 0.4 (G) 0.36.

to 10 cm/s. The H_L increases non-linearly with *U*o, by addition of helium diluent and flame was blown out for $0.2 < X_{F,O} < 0.34$. Direct photographs of lifted flames at *U*o = 14 cm/s for various fuel mole fractions $X_{F,O}$, is shown in the Fig. 2(b). For diluted propane two different stabilization modes were observed in the developing and developed regions of co-flow jets. As a reference, the length of the developing region of free jet Z_{free}, was marked by dotted line. This was estimated to be $Z_{free}/d = 0.0165$ X R_{ed} [9], where R_{ed} was the Reynolds number defined as, Uod/v where v was the kinematic viscosity. Since the fuel is diluted, v was adopted with that of helium. In Fig. 2(a) nearly linearly variation has been formed in Z_{free} with *U*o, which further substantiates the two different stabilization modes in the developed and the developing regions of jet flame. Even if, the lifted flames are formed in developing and developed regions, the stabilization mechanism has to be the balance of edge flame speed to the local flow speed.

It was observed that, these flames are lifted at smaller nozzle exit velocities less than stoichiometric unstretched laminar flame speeds and it was well explained by the buoyancy effect[4]. This effect of buoyancy was evaluated by the Richardson number as, $Ri = \rho gd/\rho U^{2}$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 ρ was the density difference between unburned and burned gases. Also, *Ri* number is evaluated for *U*o = 5-30 cm/s at different stoichiometric conditions from $0.2 < X_{F,O} < 0.5$ which is in the range of $0.8848 < Ri < 32.86$ as shown in the Fig. 2(a). Results shows that, at low *U*o, (5-9 cm/s) having high *Ri* number, buoyancy effect is more influential and hence the stationary lifted flames are formed. But with increase in the *U*o, from (10-30) cm/s the *Ri* number value decreases and buoyancy is suppressed significantly. Here it was observed that, at low *U*o lifted flames are formed due to influence of buoyancy which belongs to the developing region. But buoyancy effect goes to minimum with the increase in the *U*o.

To obtain the lifted flames at much higher nozzle exit velocities than stoichiometric un-stretched laminar flame speed, experiments were conducted using 0.95 mm i.d. nozzle co-flow burner. Co-flow velocity *V*co, was fixed to 5 cm/s. The change in H_L with *U*o for methane diluted with helium at various $X_{F,O}$ is shown in the Fig. 3(a). Liftoff height increases non-linearly

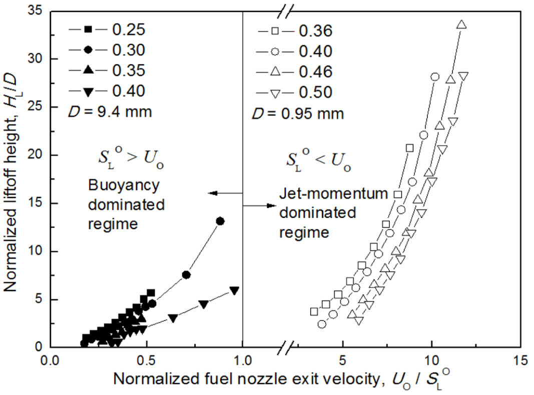

Fig. 4. Normalized liftoff height with fuel nozzle exit velocity considering stoichiometric un-stretched non-adiabatic laminar burning velocity for two different fuel nozzles.

by addition of helium diluent and with increase in the Uo. Direct photographs of lifted flames for Uo = 260 cm/s at various $X_{F,O}$ are shown in the Fig. 3(b). Richardson number Ri, was also evaluated to observe the buoyancy effect and it is in the range of $0.00009 < Ri < 0.0015$. Results shows that, buoyancy effect can be suppressed with Uo, and lifted flames were obtained at higher Uo than stoichiometric un-stretched non- adiabatic laminar flame speeds. Fig. 4, shows the normalized liftoff height with Uo, considering stoichiometric un-stretched non-adiabatic laminar burning velocity for two different fuel nozzles 9.4 mm and 0.95 mm. Using 9.4 mm i.d. nozzle co-flow burner lifted flames are obtained at lower Uo than S_L^o and for 0.95 mm nozzle diameter lifted flames are obtained at higher Uo than S_L^o. The stoichiometric un-stretched non-adiabatic laminar burning velocities were evaluated by using 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. This un-stretched non-adiabatic stoichiometric laminar flame speed was achieved through extrapolation of the linear relation of flame speed versus global strain rate in a counterflow configuration. Fig. 4, confirms that lifted flames exists for methane diluted with helium even at high Uo than S_L^o. For such cases, there are some other factors responsible for flame stabilization will be discussed later.

Also, change in H_L with Uo is shown in Fig. 5(a) for methane diluted with nitrogen ($Sc < 1$). Direct photographs of lifted flames for Uo = 20 cm/s at different $X_{F,O}$ is shown in Fig. 5(b). Even though not shown clearly flame edge has a tri-brachial structure when H_L is large, while the nozzle attached flame edge shows that the lean premixed flame wing is merged to the diffusion flame. For methane diluted with nitrogen stationary lifted flames were observed only in the developing region due to buoyancy effect at low Uo. This was confirmed by evaluating Richardson number Ri [4] at different stoichiometric condition which is in the range of $0.15 < Ri < 32.11$. Results shows that, buoyancy effect is more influential at low Uo where Ri number is large but with increase in Uo, Richardson number and buoyancy also decreased, still in this region lifted flames are formed. Further investigations may require to clarify the reason behind these lifted flames.

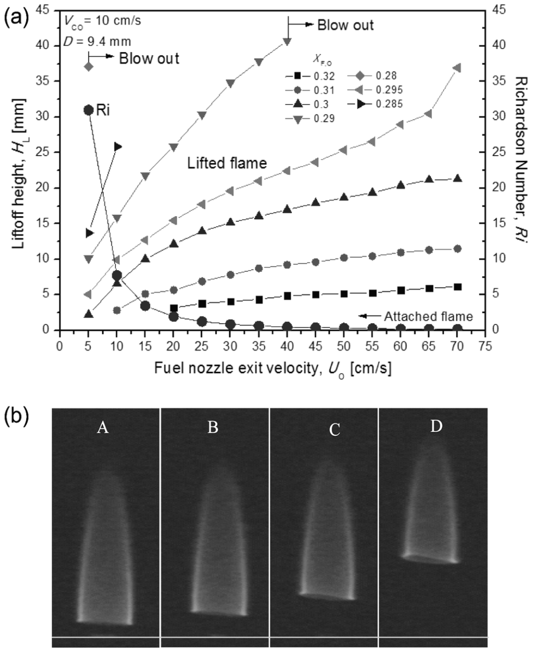

Fig. 5. (a) Change in liftoff height with fuel nozzle exit velocity for methane diluted with nitrogen ($Sc < 1$) at various fuel mole fractions and (b) direct photographs of stationary lifted methane jet flame diluted with nitrogen for Uo = 20 cm/s at (A) $X_{F,O}$ = 0.32 (B) 0.31 (C) 0.3 (D) 0.29.

3.2. Stabilization of lifted flame

In the previous discussions, it was shown that lifted flames were observed for methane jet diluted with helium and nitrogen in buoyancy dominated and jet momentum dominated regimes. So it should be known that why these lifted flames were stabilized. As the balance of edge flame speed to the local flow one is

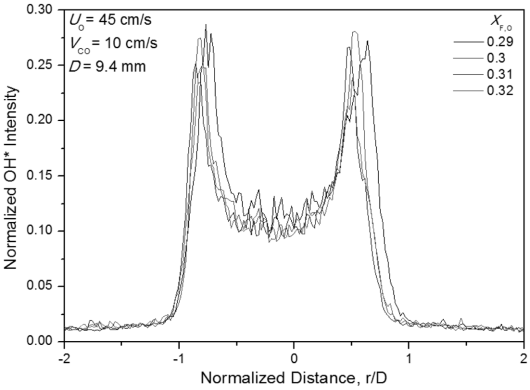

Fig. 6. Typical radial distribution of chemiluminescence intensity passing through the triple point at various $X_{F,O}$ for Uo = 45 cm/s and Vco = 10 cm/s in case of D = 9.4 mm.

stabilization mechanism then 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 captured by an intensified charge coupled device (ICCD) camera with OH optical filter and flame image processing has been done by Winspec/32 software. In which, image is an array of integers that are linearly scaled. The typical range of 8-bit intensity images is usually [0, 255]. This maximum intensity at 255 is the saturated intensity and maximum value of OH* intensity at triple point has been considered less than 255. Chemiluminescence intensities of OH* (good indicators of heat release rate) [7] radical are measured at various conditions. Typical radial distribution of OH* chemiluminescence intensity passing through the triple point at various conditions is shown in the Fig. 6. 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. Based on them maximum OH* chemiluminescence intensities were examined at various $X_{F,O}$ and Uo. Fig. 7, shows the measured OH* radical chemiluminescence intensities for (a) methane diluted with helium at Uo = 30 cm/s and (b) methane diluted with nitrogen at Uo = 35 cm/s, for various $X_{F,O}$ using 9.4 mm diameter nozzle, and thereby corresponds to buoyancy dominated regime as shown in the Fig. 4. Results demonstrates that, increasing mole fractions of helium and nitrogen increases the normalized maximum OH* intensities which 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.

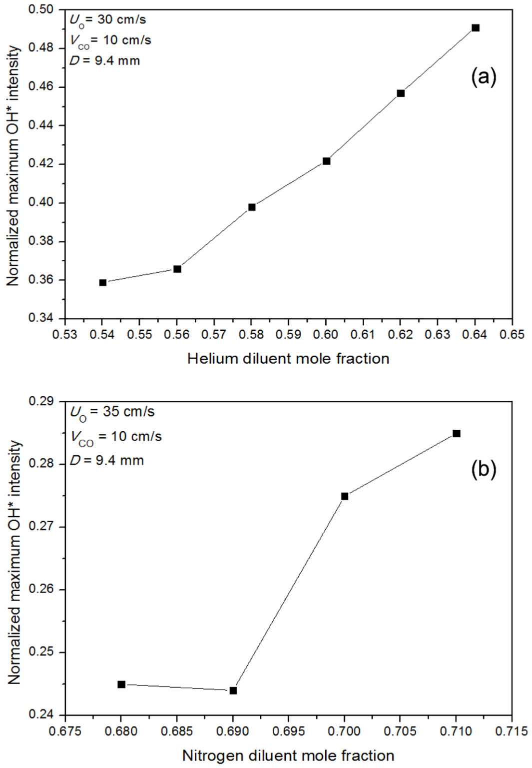

Fig. 7. Measured OH* radical intensities for (a) methane diluted with helium at Uo = 30 cm/s and (b) methane diluted with nitrogen at Uo = 35 cm/s, for various $X_{F,O}$ using 9.4 mm nozzle diameter.

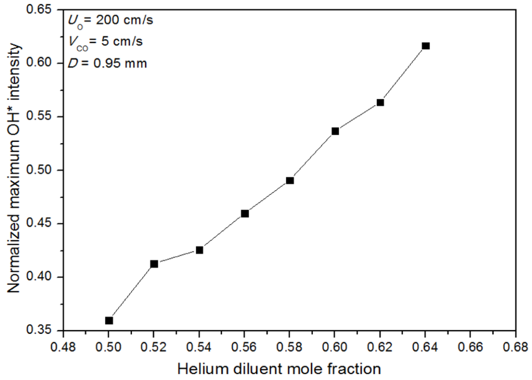

Fig. 8. Measured OH* radical intensities for methane diluted with helium at Uo = 200 cm/s and various $X_{F,O}$ using 0.95 mm nozzle diameter.

Similar investigations were observed for D = 0.95 mm diameter nozzle co-flow burner at Uo = 200 cm/s as shown in the Fig. 8. With increase in the helium mole fraction normalized maximum OH* intensity in

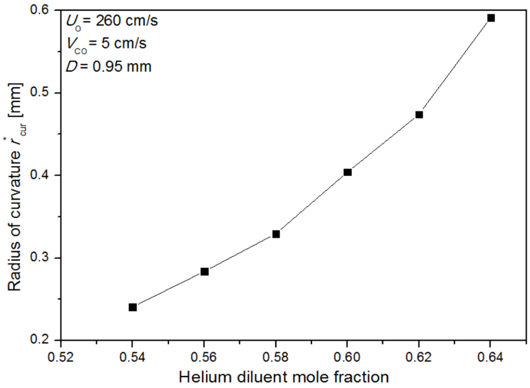

Fig. 9. Radius of curvature r^*_{cur}, of lifted methane jet flame with the addition of helium dilution by using 0.95 mm nozzle diameter.

creases and Richardson number is negligible for such a high nozzle exit velocity (which corresponds to jet momentum dominated regime). Such a tendency may not be explained by the buoyancy effect meaning that there are some other reasons. Although it is not provided that, at a fixed strain rate in a counterflow configuration, OH* concentration decreases with diluents mole fraction of He and N_2. Then enhancement of edge flame speed through chemical effects is not plausible in reasoning such phenomena. Neverthele-ss, the feasibility in high temperature ambience will remain in future work because the stabilization mechanism has a jump from the balance of edge flame speed to the local flow speed at normal temperature ambience to reduction in ignition delay time at high temperature ambience. Also edge flame speed has the dependancy upon the mixture strength, buoyancy, fuel concentration gradient (strain rate and thereby radius of curvature), and Lewis number. Because mixture strength decreases with diluent addition, it has a negative effect in flame stabilization. The range of the Lewis number is 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 on edge flame speed such that, the Lewis number increases with helium mole fraction. This means that, 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 the appreciable increase in r^*_{cur}, with helium mole fraction in jet momentum dominated regime, thereby increasing edge flame speed.

4. Conclusion

The stabilization mechanism of laminar lifted methane jet flame diluted with helium and nitrogen ($Sc < 1$) has been investigated experimentally. These 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 $U\text{o} < S_L^o$. 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 by increasing the reaction rate and edge flame speed. However, for 0.95 mm nozzle diameter lifted flames were existed in jet momentum dominated regime. It was found that, in such lifted flames, appreciable increase of radius of curvature in addition to increased OH* concentration contributed to the stabilization.

Acknowledgement

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science, and Technology (2014-2015).

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