층류 비예혼합 수소/메탄 제트화염의 부상특성에 관한 수치적 연구

김승욱* · 정기성* · 정석호** · 유춘상*†

A Numerical Study of Liftoff Characteristics of Laminar Nonpremixed Hydrogen/Methane Jet Flames

Seung Ook Kim*, Ki Sung Jung*, Suk Ho Chung**, Chun Sang Yoo*†

ABSTRACT

The liftoff characteristics of laminar nonpremixed hydrogen/methane jet flames are numerically investigated using OpenFOAM. It has been reported from various experiments that auto-ignited lifted flame at the low temperature regime has a unique characteristic such that the liftoff height decreases with increasing fuel jet velocity. The numerical results show qualitative agreement with the experiments, and the decreasing tendency of liftoff height can be attributed to the differential diffusion of methane and hydrogen.

Key Words : Lifted flame, Autoignition, Laminar flame, OpenFOAM

Global warming is one of the most significant issues in these days, and regulations on exhaust gases are becoming stringent to cope with the issue. In this regard, hydrogen-enriched natural gas, or HCNG, is highlighted as a clean combustion fuel. Low pollutant emissions and improving flame stability are HCNG's main advantages. In case of the methane jet flames of co-flow air, especially, adding hydrogen in fuel side helps lifted flame to reduce its liftoff height such that flame can be stabilized easily.

In previous experiments [1], it was found that auto-ignited lifted flame at a relatively-low temperature regime has a unique characteristic in the way that liftoff height decreases as fuel jet velocity increases. Such behavior was not observed previously, and the reason has not been fully explained yet.

The objective of this study is to carry out numerical simulation to elucidate the unique combustion behavior with OpenFOAM, which is a open-source computational fluid dynamics software.

A skeletal mechanism [2] is applied having 30 species with 184 reactions. The given domain is 6.65 x 30cm in radial (x) and axial (y) coordinates with 115 x 1500 grids and jet radius is 1.9mm with 0.5mm nozzle thickness. In radial direction, 50 uniform grids are employed within 1cm from the center ($\triangle x \sim$ 200μm), and remaining grids are non-uniformly distributed in the outer domain. In axial direction, 1500 grids are uniformly distributed ($\triangle y \sim 200\mu m$).

According to the previous numerical simulation [3], which is carried out for diluted methane in co-flow air with the same geometry as present study, temperature needs to be about 100K higher than the experimental condition in order to obtain the similar liftoff height of experiment results. In this simulation, therefore, fuel and air inlet temperature are decided to increase to 950K whereas decreasing liftoff height behavior was detected at low temperature regime(860~920K).

Other boundary conditions are as same as experimental condition [1], and described in table 1.

* 울산과학기술원 기계공학과
** KAUST Clean Combustion Research Center
† 연락저자, csyoo@unist.ac.kr
TEL : (052)217-2322 FAX : (052)217-2409

Table 1 Boundary Conditions

Fuel jet velocity (U_0)	15, 20, 25 (m/s)
Coflow air velocity (Ucoflow)	1.1 (m/s)
Pressure	inlet = Zero Gradient outlet = 1 atm
Fuel mole fraction (X_F)	0.2
Hydrogen ratio (R_h)	0.3

After applying non-reacting flow for sufficient time, reacting flow is calculated until the flame will be stabilized within the given domain. lift-off height is defined as length from jet to flamebase where OH mass fraction value is 1.0e-4. From low to high jet velocity case; U_0=15m/s (case L) U_0=20m/s (case M) U_0=25m/s (case H), lift-off height are 0.233m, 0.221m and 0.213m respectively. Temperature and OH mass fraction profile for all cases are described in Fig. 1 and Fig. 2.

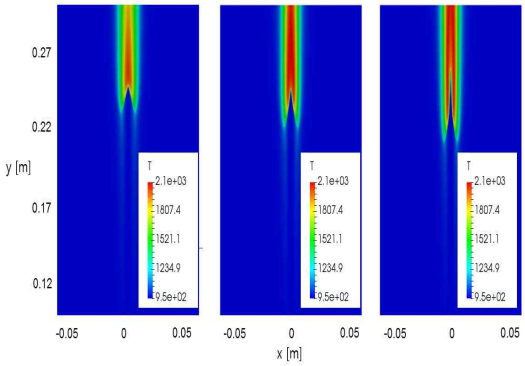

Figure. 1 Temperature profile of laminar lifted flame. U_0 = 15(m/s), 20(m/s), 25(m/s)

All cases have tribrachial edge flame structure and edge flame speed for three cases are 2.452m/s (case L), 2.486m/s (case M) and 2.508m/s (case H).

Figure 3 shows the radial profile of mole fractions at y=0.2m where upstream of flamebase for all cases. Solid vertical line represents location of local maximum temperature and dashed line indicates location of stoichiometry. It is interesting to note that all species have peak value at the lean side where the local maximum temperature occurs. These results coincide with previous research [3].

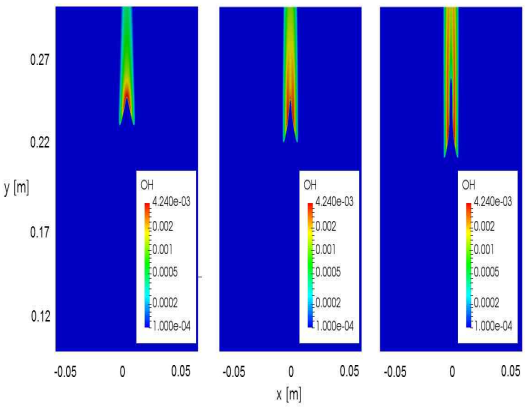

Figure. 2 OH mass fraction profile of laminar lifted flame. U_0 = 15(m/s), 20(m/s), 25 (m/s)

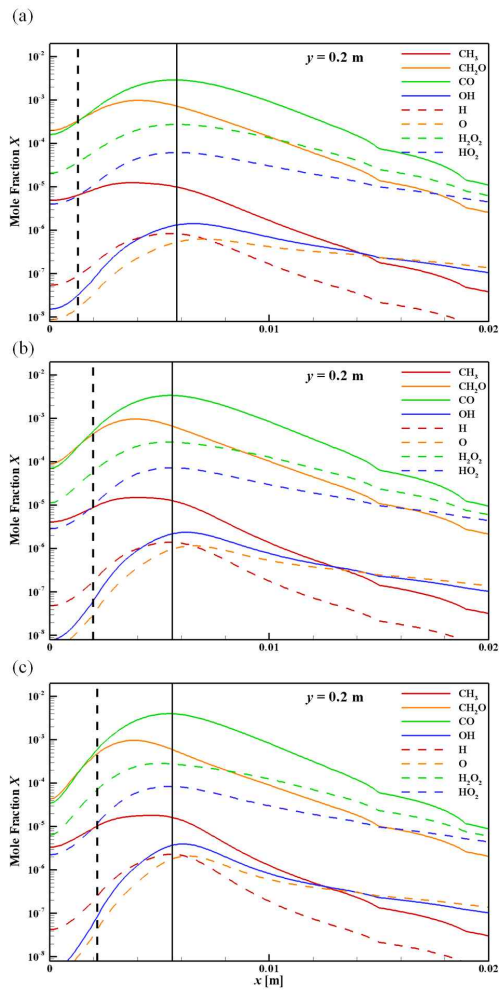

Figure. 3 Species mole fractions of case L, M and H (from top to bottom) at y=0.2m

The lean side of ignition delay is shorter than the stoichiometry's. It explains why maximum T occurs at lean side and autoignition occurs away from stoichiometry. It has been found that tribrachial flame is formed by both autoignition and flame propagation mode. Flame propagation mode is predominant at the downstream region. On the contrary, autoignition mode is dominated at the upstream of flamebase. (A description of tribrachial flame structure is explained in [3]). Therefore, lift-off height of tribrachial flame is mainly related with the ignition delay time [4,5], In autoignition mode of HCNG, ignition delay time decreases with the increase of hydrogen ratio R_h, which is defined as $X_{H2}/(X_{CH4}+X_{H2})$.

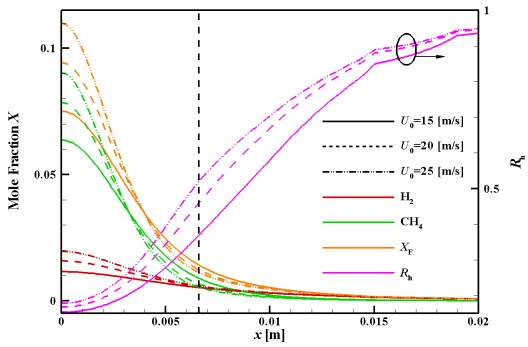

Figure. 4 H_2, CH_4 mole fractions of autoignited tribrachial flame at y=0.2m. Vertical dashed line indicates flame edge x-directional location.

In Fig. 4, radial distributions of H_2 and CH_4 at upstream region (y=0.2m) are plotted. Vertical dashed line indicates a flame edge x-directional location (x=6.6mm) where the diffuse effect of jet is negligible; flame edge are located almost same region with respect to x-direction. Near the flame edge region, mole fraction of methane decreases as jet velocity increase whereas hydrogen does not be reversed regardless of velocity variation. This is because methane has a lower diffusivity as compared to hydrogen, thus the amount of methane going to the flame edge region reduces as jet velocity increases. Consequently, hydrogen ratio R_h will increase with jet velocity at the flame edge region and liftoff height decreases accordingly. (R_h=0.37, 0.46, 0.52 at U_0=15m/s, 20m/s, 25m/s, respectively). According to the 0-D homogeneous autoignition case, ignition delay time at the upstream of flame edge region is 0.0380s 0.0365s 0.0362s at U_0=15m/s, 20m/s, 25 m/s. As expected, ignition delay time is going to be shorter as jet velocity becomes faster and that would be caused by increasing tendency of hydrogen ratio, R_h.

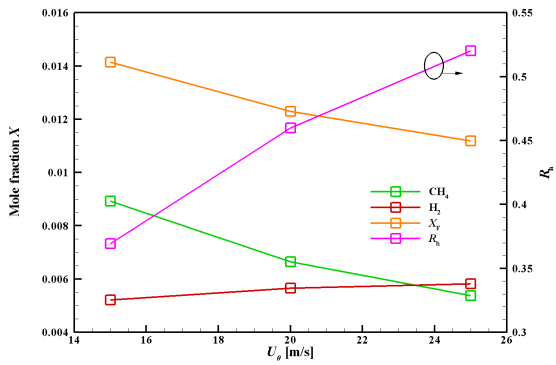

Figure. 5 H_2, CH_4 mole fractions at upstream of flame edge (x=6.6mm, y=0.2m).

Figure 5 shows the species mole fraction and hydrogen ratio for each case at the upstream of flame edge. Methane mole fraction decreased as jet velocity increased that induce increasing hydrogen ratio as jet velocity increased. The reversed point of methane mole fraction locates richer side than flame edge location because of diffusivity difference of species. The ignition delay of HCNG decreases as R_h increased. The chemical structure at upstream of flamebase shows the autoignition mode is dominant. Despite of large jet velocity, short ignition delay affects formation of short lift-off height.

Conclusion

In this study, hydrogen/methane laminar lifted flame at 950K with 3 different fuel jet velocity were simulated. Lift-off height is decreased as fuel jet velocity increased. Chemical structure shows that all cases have the tribrachial edge flame structure and autoignition occurs upstream of flamebase. The ignition delay of lean region is shorter than stoichiometry, this

affects location of flame edge and local maximum temperature occurs lean side. Diffusivity difference of species make R_h to be decreased as jet velocity increases. At the upstream, large value of R_h affects small lift-off height despite of large jet velocity.

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