Effects of Applied Electric Fields on Liftoff Height in Laminar Lifted Coflow-jet Flames

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1. Introduction

Since the first works on laminar lifted tribrachial flame in jet configuration [1-2], the behaviors of free- and coflow-jet flames have been widely studied, because the fundamental characteristics are useful in extended laminar stretched flamelet modeling and also in designing industrial burners [3-7]. Such a lifted flame configuration propagates along the stoichiometirc contour such that flame speed is balanced to the local flow one for Shumit number, *Sc* larger than unit. However, Won et al showed through experiments in normal gravity and numerical simulations in normal- and microgravities that nitrogen-diluted methane coflow-jet flames have been lifted in increase of nozzle exit velocity U_O, and verified that such lifted flames were caused by buoyancy effects in the near field of coflow jets even for $Sc < 1$. It was recently noted that liftoff height H_L decreased with increasing U_O in highly diluted nitrogen cases [8]. It was also recognized that this anomalous lifted flame was caused by buoyancy and radiation heat loss and confirmed numerically by varying gravitational level and by modulating radiative heat loss via variation in absorption coefficients [8].

Considerable research efforts have been devoted to understanding electrical properties of flames and how they can be manipulated by electric fields. Lawton et al investigated that applied an electric field to flame could alter various combustion characteristics through the acceleration of charged particles by the Lorentz force [9]. They also found that the acceleration could cause the drift velocity and lead to the increase in kinetic energy such that the mobility and chemical reaction associated with charged particles can be enhanced. Meanwhile, the effects of applying electric fields to non-premixed flames through single-electrode configuration in laminar coflow jet was investigated [6, 7]. The detachment velocity could be extended appreciably by applying the AC voltage to the fuel nozzle. This results also showed that the propagation speed was also observed to be increased appreciably. However, the effects of electric fields

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with AC and DC on flame behaviors in a regime to have a tendency of decreasing liftoff height with fuel nozzle exit velocity have not been explored previously. Thus, the present study aims to investigate the effect of applying AC electric fields to lifted flame in the regime to have the tendency of decreasing H_L against fuel nozzle exit velocity as an extended work of the previous work [8].

2 Experimental facility

Figure 1 shows the schematics of experimental setup and flow system in a coflow-jet burner configuration. The experimental apparatus consisted of a nozzle system, a flow system, a coflow-jet burner, an electric field generation system, and a visualization system. The coflow-jet burner had a central fuel nozzle made of stainless steel (i.d. 0.95 mm and o.d.1.33 mm). The nozzle length was 210 mm enough to ensure fully developed parabolic velocity profiles at the fuel nozzle exit, and the nozzle tip was located 10.8 mm above the coflow exit. The Reynolds numbers, based on fuel tube nozzle and cold exit condition, were in ~~the~~ range of $37.09 \leq Re_D \leq 125.04$, such that. The fuel steams, taken from Schlieren visualizations, were of typical laminar flows. Methane and nitrogen in the fuel stream and coflow-air with purities of 99.999% were used, respectively. The flow rates of those reactants were controlled precisely by using mass flow controllers and Flow Manager software (version 3.3). A series of glass beads and honeycomb were installed to obtain uniform of coflow-air velocity. To avoid external disturbance, a cylindrical acrylic with i.d. 92.6 mm and 500 mm in length was installed at the exit of coflow air. The coflow-air velocity, V_{CO}, was fixed to 7 cm/s. Both AC and DC powers were supplied by a Trek,10/10B-HS. In the case of AC, the applied frequency was in ~~the~~ range of 60 – 1000 Hz and the voltage was applied up to 1 kV in the RMS value. An oscilloscope (Tektronix, TDS 1012) was used to monitor applied voltage and frequency. One electrode from the AC power supply was connected to the fuel nozzle and the other electrode was grounded to the building. Flame images were taken by a digital camera (SONY HDR CX-560) installed over a 2-D transfer device. A Matlab-base code was used to analyze the flame images. Flame lift-off height was defined as the brightest point on the flame front in the image converted into a gray one.

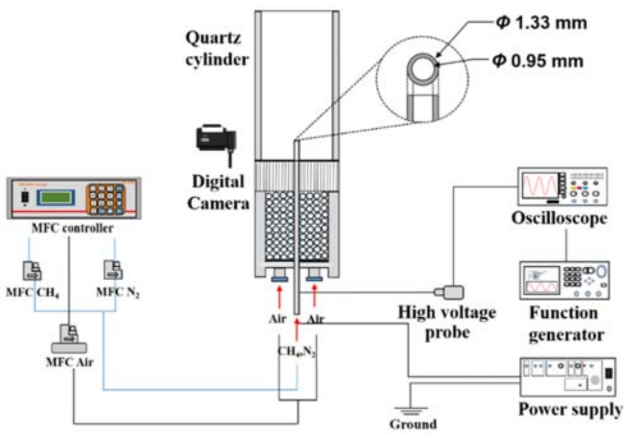

Figure 1. Schematic of the experimental setup.

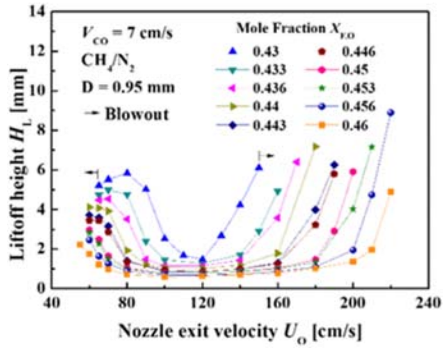

Figure 2. Liftoff height against nozzle exit velocity at V_{CO} = 7 cm/s for D = 0.95 mm in nitrogen-diluted coflow jet methane flame with no electric field.

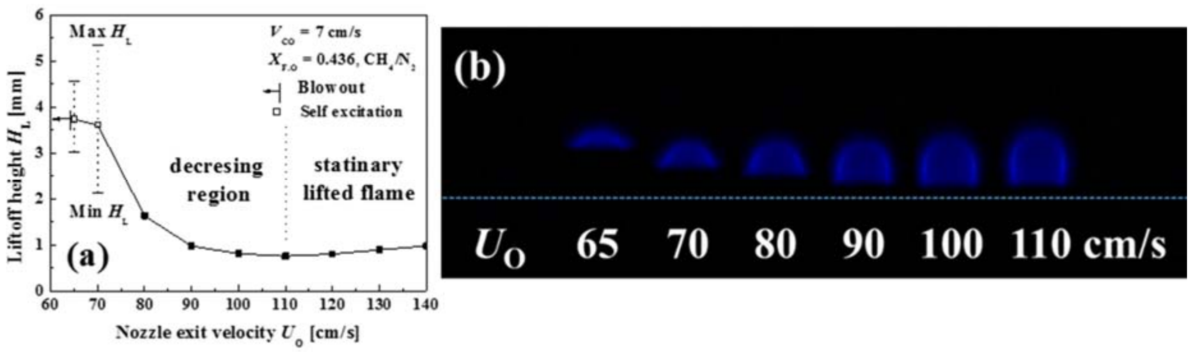

Figure 3. (a) Liftoff height against nozzle exit velocity at V_{CO} = 7 cm/s and $X_{F.O}$ = 0.436 for D = 0.95 mm in nitrogen-diluted coflow jet methane flame with no electric field and (b) corresponding direct images.

3 Result and Discussion

Figure 2 shows variation in lift-off height, H_L, as a function of fuel mole fraction, $X_{F,O}$, at V_{CO} = 7 cm/s for the baseline case with no electric field. The results show that lifted flames exist even for $Sc < 1$ at various $X_{F,O}$ and U_O. Two kinds of lifted flame exist: H_L in increase of U_O increases for U_O > 110 cm/s (called H_L-increasing regime) and decreases for U_O < 110 cm/s (called H_L-decreasing regime). These results coincide with those in the previous study that the existence of such a stationary lifted flame in nitrogen-diluted methane coflow-jet flames was addressed to buoyancy effects in H_L-increasing regime whereas in H_L-decreasing regime, it was attributed to radiation heat loss along with buoyancy [8]. The latter was ~~also~~ observed at very low $X_{F,O}$ and U_O for D < 9.2 mm. Figure 3 demonstrates variation in H_L against U_O and correspondent images of lifted flame with U_O at $X_{F,O}$ = 0.436 with no electric field, respectively. As shown in Fig. 3, in the case of U_O < 110 cm/s, the H_L in increase of U_O decreases monotonously and then attaches to the nozzle.

Figure 4 exhibits variations in H_L against U_O in terms of f_{AC} ($f_{AC} \leq$ 1000Hz) at $X_{F,O}$ = 0.436 and V_{CO} = 7 cm/s for V_{AC} = 100 (a), 300 (b), 600 (c), and 900 V (d). Open symbols denote the flame conditions for self-excitation. For V_{AC} = 100 V (a), when AC frequency applied to lifted flames for baseline cases in H_L-decreasing regime, H_L decreases slightly up to 700 Hz and appreciably at 900 Hz, compared with that for

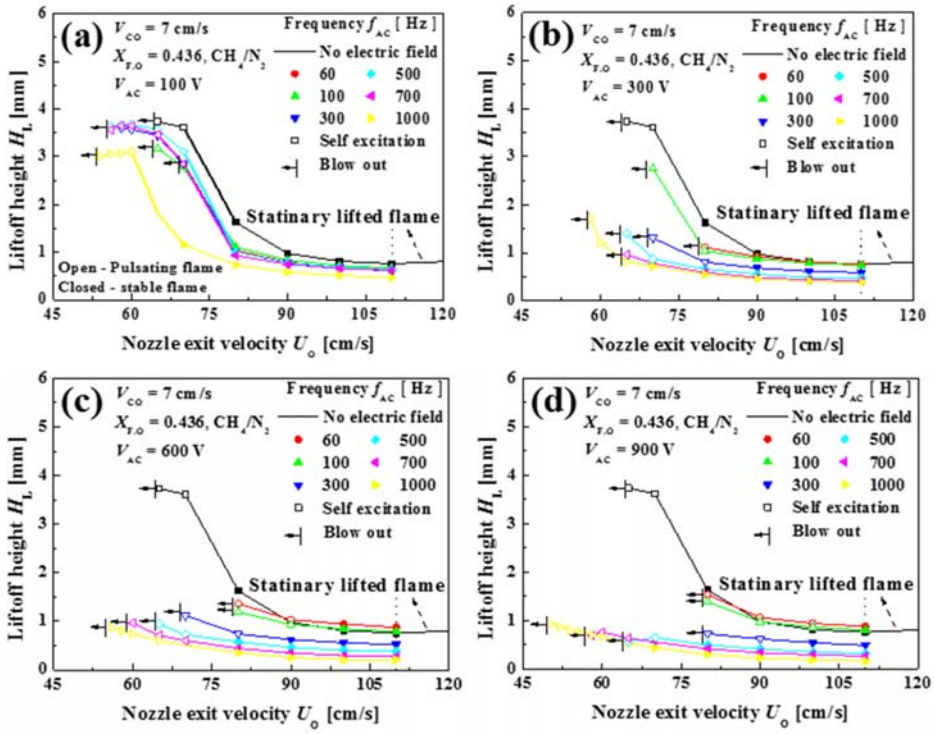

Figure 4. Variations in liftoff height as a function of nozzle exit velocity at various frequencies for fixed voltages; V_{AC} = 100 V (a), 300 V (b), 600 V (c) and 900 V (d).

the baseline case. Also, blowout limit does not vary for $f_{AC} \leq 300$ Hz but is extended appreciably to lower U_O for f_{AC} >300 Hz. For V_{AC} = 300 V (b), H_L decreases slightly for $f_{AC} \leq 100$ Hz and appreciably for f_{AC} > 300 Hz. Blowout limit is shrunk to higher U_O for $f_{AC} \leq 60$ Hz, is restored to that for the baseline case for 60 < $f_{AC} \leq 700$ Hz, and then is extended to lower U_O for f_{AC} = 1000 Hz. For V_{AC} = 600 and 900 V (c, d), blowout limit is also shrunk to higher U_O for $f_{AC} \leq 100$, is extended again in further increase of f_{AC}. For V_{AC} > 300 V, H_L decreases appreciably for all applied frequencies. Blowout limit was reduced to higher U_O at f_{AC} < 500Hz for 600 (c) and 700 V (d), while it was extended at f_{AC} = 1000 Hz. Consequently, there exists a critical frequency, f_c, for a fixed voltage less than 1 kV, e.g., f_c = 500 Hz for 600 and 700V over (below) which flame stabilization is enhanced (suppressed). It is also found that once AC electric fields are applied to those lifted flames, liftoff heights are reduced appreciably before flame blowout. Such a reduction in liftoff height with applying electric fields may be addressed to increase in edge flame speed [12]. However, it may be further required to understand the effects of with applied electric filed on lifted flame behavior.

Figure 5 demonstrates axial distributions of OH* chemiluminescent intensity passing through the triple point (identified as the maximum intensity) at various frequencies for V_{AC} = 900 V, V_{CO} = 7 cm/s, and $X_{F.O}$ = 0.436. Note that OH* chemiluminescent intensity can be used as an measure of the heat release rate [13]. The results show that increasing f_{AC} rather reduces maximum OH chemiluminescent intensity. This implies that increasing f_{AC} does not increase edge flame speed in H_L-decreasing regime even if it reduces liftoff height as shown in Fig. 4. Thus, further experimental works and analysis should be done to understand them, and will be a future work.

Now it may be required to characterize the liftoff heights in H_L-decreasing regime with functional dependencies of related physical parameter, and is shown in Fig. 7. The liftoff heights in H_L-decreasing regime are best-fitted to

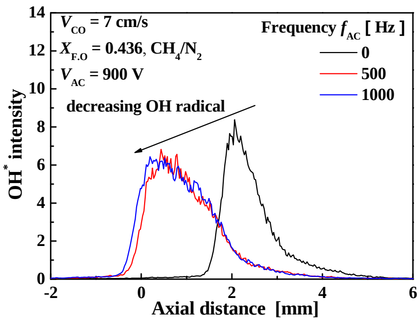

Figure 5. Axial distribution of OH* chemiluminescent intensity passing through triple point at various frequencies for V_{AC} = 900 V, V_{CO} = 7 cm/s, and $X_{F.O}$ = 0.436.

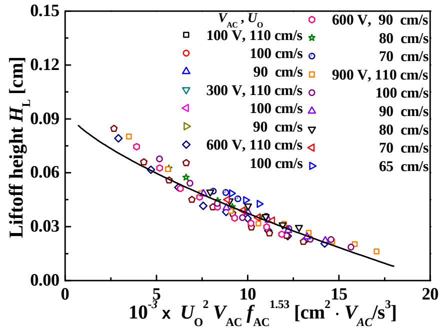

Figure 6. The Correlation among liftoff heights, voltage, and frequency.

$$H_L = 0.0001 \times a\lambda^b + c \text{ (with a correlation coefficient of 0.927).} \quad (1)$$

Here, a = - 0.116, $\lambda = U_O^2 V_{AC} f_{AC}^{1.53}$, b = 0.314, and c = 0.0955. However, further confirmation through experiments with various nozzle diameters will be a future work.

4 Conclusions

Experimental study has been conducted to grasp the effect of AC elctric fields on lifted flame behavior in H_L-decreasing regime in nitrogen-diluted methane coflow-jet flames. Lifted flames in H_L-decreasing regime were influenced appreciably by applied electric fields. Applying AC electric fields reduced liftoff heights appreciably compared with those for the baseline cases with no elxtric field. However, there existed a critical frequency, f_c, for a fixed voltage less than 1 kV, over (below) which flame stabilization is enhanced (suppressed). Such liftoff heights were characterized well by some physical parameters such as nozzle exit velocity and applied frequency and voltage. Interestingly, such a reduction in liftoff height with applying AC electric fields could not be addressed to enhancement of edge flame speed, and further confirmation will be a future work.

Acknowledgements

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