A Study on Comparison of Lewis-number-induced with Buoyancy-driven Self-excitation in Laminar Lifted Coflow-Jet Flames.

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Abstract

A study on laminar jet flames in coflow air diluted with helium has been conducted to investigate self-excitations for various propane mole fractions and nozzle exit velocities. The stability map was represented as a function of nozzle exit velocity and fuel mole fraction for propane. The results show that two types of self-excitation were observed : (1) buoyancy-dreiven self-excitation and (2) Lewis-number-induced self-excitation coupled with (1) near extinction limit for 9.4mm nozzle diameter. It was shown that with 0.95mm nozzle diameter, Lewis-number-induced and buoyancy-driven self-excitations could be sperated. The differences between the two self-excitations were addressed and discussed.

Introduction

Since the first spot of laminar tribrachial flame in lifted jet configuration [1, 2], the behaviors of free- and coflow-jet flames have been successfully described by the cold jet similarity concepts [2]. Such a laminar lifted flame in free- and coflow-jet configurations propagates along a stoichiometric contour due to the intrinsic nature of tribrachial structure such that the flame speed is balanced to the local flow one. The tribrachial flame speed depends upon the mixture strength, Lewis number, heat loss, fuel concentration gradient, and buoyancy. Because of such a stabilization mechanism of tribrachial flame, the lifted flame could be self-excited by some factors of them that modify the edge flame speed, i.e. buoyancy due to a flame flicker, the repetitive interaction of burning rate and buoyancy-driven convection and conductive heat loss from premixed wings to trailing diffusion flame.

Won et al [3] and Füri et al [4] investigated self-excitation with the similar frequencies of $O(1)$ Hz in laminar lifted coflow-jet flames, and identified as buoyancy-induced and Lewis-number-induced self-excitations (hereafter called BDSE and Le-ISE), respectively. The extended work through the comparison of normal- and micro-gravity experiments as well as numerical simulation verified that the self-excitations were caused by the repetitive interaction of burning rate and buoyancy-induced convection [5]. It has been believed to preclude all doubts since that. Nonetheless, it was noted that the self-excitation of tribrachial flame due to Lewis number in 2D mixing layer configuration had been described well numerically in zero gravity [6]. It was also recognized that heat-loss- induced self-excitation (hereafter called HLISE) (f < 0.1 Hz) suppressed the BDSE in nitrogen-diluted non-premixed free-jet propane and butane flames [7]. With those backgrounds, Lee et al tried to distinguish the Le- ISE from the BDSE in nitrogen-diluted laminar non-premixed free-jet flames with an applied DC electric field of V_{DC} = -10 kV [8]. Applying the DC electric field increased tribrachial flame speeds significantly and thereby forced the flame to be attached to the nozzle, such that HLISE could not appear. They also found that the Le-ISE can be suppressed evidently by the BDSE in the existence of buoyancy. By applying a horizontal injection method (in order to eliminate the accumulated partially premixed mixture in front of tribrachial flame and thereby buoyancy effect), it was shown that the Le-ISE could be separated from the BDSE, and also found that characteristics of the Le-ISE were very similar to those observed numerically by Kurdyumov et al [9, 10] in 2D mixing layer configuration. However, disadvantage of the experimental study was to apply the DC electric field and also to observe the Le-ISE not in lifted flame but in attached flame. Then, further experimental efforts may be required to find the existence of Le-ISE without applying electric fields and to further embody the characteristics in laminar lifted jet flame.

Experimental facility

The experimental apparatus schematically shown in Fig. 1 consisted of a coflow-jet burner, mass flow controller, a digital camera system and a visualization system. Two types of fuel tube nozzle (9.4 and 0.95 mm in diameter) in coflow-air jet configuration with 60.0 mm

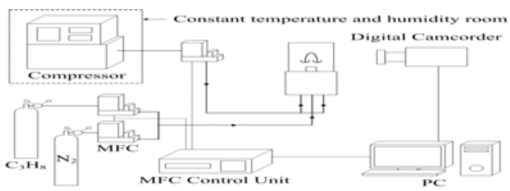

Figure 1. Schematic experimental setup and flow system about coflow-jet burner configuration.

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in outer diameter were used. Propane with a purity of 99.99 %, and helium and nitrogen with purities of 99.99 and 99.95 % were used, respectively. The fuel tube 100 cm in length such that the internal flow can be fully developed. The flow rates were controlled precisely by using mass flow controllers with maximum flow capacities of 50, 100, 500, 20000, 50000 ml/min, and a Flow Manager software (version 3.2). Their nominal accuracies for the full-scale flow rate were within of 1.0 %. A series of glass beads were installed in the lower half of the compartment to suppress external disturbances and to obtain uniform outer jet flows. A cylindrical acrylic compartment with 10 cm diameter and 40 cm length was used to reduce external derangement as well. Experiments were conducted by adding helium with a high thermal conductivity to the outer coflow air to control heat losses from the flames to ambience. Compressed air whose humidity (41 ~ 43 %) and temperature (23 ºC) were controlled in a constant temperature, humidity room was also used to eliminate the uncertainty. The lift-off height was measured with a digital camera (SONY,HDR-CX560) attached to a 2-D transfer device. A Matlab-based code was used to analyze flame images. Flame length and lift-off height were defined as the brightest point in converted gray-level images of flame edge.

Results and discussion

Experiments in propane jet flames diluted with nitrogen were performed for various nozzle exit velocity U_O, fuel mole fraction $X_{F,O}$ and coflow V_{CO} was fixed at 9.4 cm/s. Figure 2 shows flame stability map as functions of U_O and $X_{F,O}$ with D = 9.4 mm. Two types of self-excited flames were observed: (I) BDSE existed at $X_{F,O} >$ 0.1 and (II) Le-ISE coupled with BDSE (hereafter called LCB, regime II) appeared at $0.1 < X_{F,O} < 0.135$, similarly to those in the previous studies. Stoichiometric laminar flame speeds were in range of 20.6 – 26.0 cm/s at $0.1 < X_{F,O} < 0.135$, and the nozzle exit velocity was also smaller than the stoichiometric laminar flame speeds. In this situation, the BDSE could appear due to the repetitive interaction of burning rate and buoyancy-induced convection [4]. Meanwhile the LCB was observed at very low $X_{F,O}$ (highly diluted with nitrogen), such that self-excitation appeared just prior to flame extinction when fuel Lewis number was much larger than unity and radiation of heat loss was excessive near the extinction Damköhler number [4, 9]. Based on

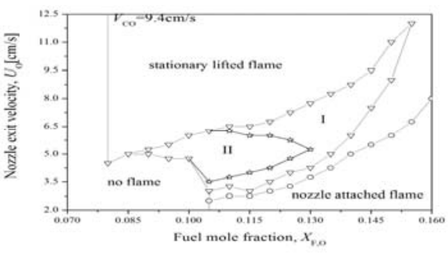

Figure 2. Flame stability map as a function of exit velocity and fuel mole fraction for D = 9.4 mm, and V_{CO} = 9.4 cm/s.

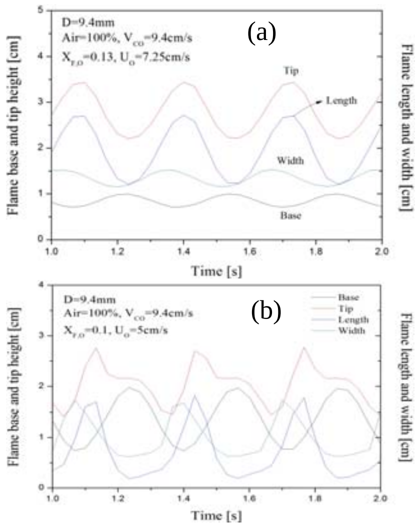

Figure 3. Various flame dimensions of BDSE (a) at $X_{F,O}$ = 0.13, U_O = 7.25 cm/s, and V_{CO} = 9.4 cm/s, and LCB (b) at $X_{F,O}$ = 0.10, U_O = 5 cm/s, and V_{CO} = 9.4 cm/s.

aforementioned study, the Damköhler numbers of LCB and BDSE may be required to be compared as well in the current study. Here, the Damköhler number was defined as:

$$D\alpha = \frac{\tau_d}{\tau_c} = \frac{W / U_O}{\delta_{f,t} / S_L^o |_{st}} \qquad (1)$$

Here S_L^O is calculated using the PREMIX code [11] with the USC mechanism [12]. The flame width and thickness denote W and $\delta_{f,t}$, respectively. The flame properties were also calculated using the USC Mech II. In case of LCB, these results show that increasing nitrogen mole fraction could force the chemical time to become larger, effectively leading to reduction of the Damköhler number. This can be in consistent with the fact that the Le-ISE was launched when the Damköhler number decreased in the previous numerical simulations [6]. To distinguish the different behavior between BDSE and LCB, variation of flame dimensions with time was investigated in Fig. 3. The self-excitation frequency in the BDSE was 3.13 Hz. The flame tip height and the flame length in the case of BDSE in Fig. 3(a) are shown to be in phase, whereas the flame tip and base heights are out of phase (the phase between the heights to flame base and tip is 180º). Such characteristics are very similar to those for the BDSE observed in the previous studies [3]. However, in case of LCB in Fig.3(b), the phase of flame tip height is unmatched to the flame base height (the phase between the heights to flame base and tip is not 180 º), while the flame tip and length are in phase. Also, the LCB frequencies are similar to those for BDSE, i.e. 3.09 Hz. To investigate the differnce between BDSE and LCB, Mie-scattering technique was used, based on the previous study [9, 10] that edge flame was self-excited due to excessive radiation heat loss near the extinction Damköhler number.

Figure 4 shows direct images BDSE and LCB thro-

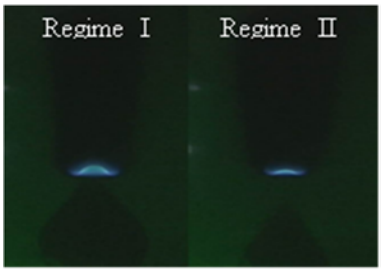

Figure 4. The direct images of BDSE and LCB through Mie-scattering technique (I) at $X_{F,O}$ = 0.13, U_O = 7.25 cm/s, and V_{CO} = 9.4 cm/s, and (II) at $X_{F,O}$ = 0.1, U_O = 5 cm/s, and V_{CO} = 9.4 cm/s for 9.4 mm nozzle diameter.

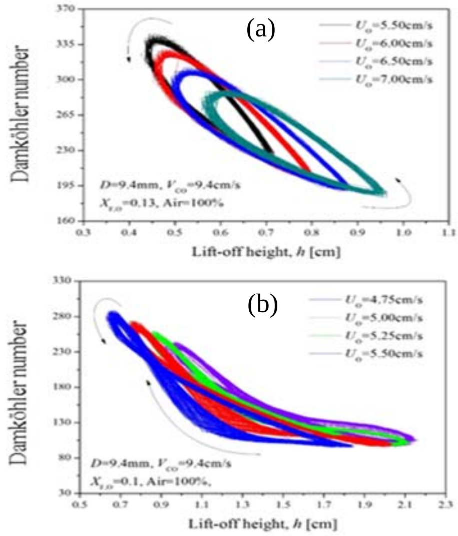

Figure 5. The functional dependency of Damköhler number on lifted-off height for various exit velocities.

-ugh the Mie-scattering technique. Particulary in the case of LCB in regime II, the fuel concentration gradient just in the front of edge flame may be very low, in that the fuel stem is very faint. This means that the flame strength of trailing diffusional flame can be very weak since only a small amount of fuel and oxidizer could be penetrated into the trailing diffusional flame, thereby losing the conductive heat from premixed wings to the trailing diffusion flame. This results is similar to the facts that the critical Lewis number for Le-ISE can be reduced if heat is lost from flame and such a flame with excessive heat losses could be self-excited [9, 10].

To further clarify the difference between BDSE and LCB, the functional dependency of Damköhler number on lifted-off height for various nozzle exit velocities is represented in Fig. 5; (a) BDSE at $X_{F,O}$ = 0.13 and (b) LCB at $X_{F,O}$ = 0.1. In cases of BDSE in Fig. 5(a), the shape is of a simply connected ellipse; the flame moves in the counterclockwise direction and this shape merely shifts in increasing nozzle exit velocity without changing its shape. In cases of LCB in Fig. 5(b), it has a multiple connected twisted shape; the flame moves upstream in the clockwise and then downstream in the counterclockwise; furthermore, the Damköhler numbers are much smaller compared to BDSE. (Particularly at downstream locations, these are one-order-lower

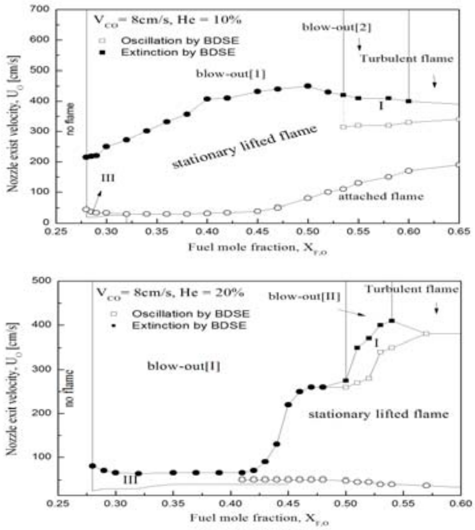

Figure 6. Flame stability maps for D = 0.95 mm and V_{CO} = 8 cm/s.

than those in BDSE). Based on the previous and present results, further experiments may be required to be conducted with much smaller burner diameters, in that it can be suppress buoyancy effects, and much higher (smaller) nozzle exit velocities (jet width) can be attained. Resultantly, the Damköhler numbers can be reduced appreciably as implied in eq. (1), so that observing the self-excitations found by Füri et al is facilitated prior to flame extinction [4] and appeared at low effective Damköhler number [10]. To control conductive heat losses from the flame to ambience, experiments were conducted by adding helium to the outer coflow air. Figure 6 shows the flame stability map represented as a function of U_O and $X_{F,O}$ in propane jet flames with coflow-air diluted with helium (10 and 20 %) for 0.95 mm nozzle diameter. The results exhibit that BDSE is observed at relatively higher fuel mole fractions (0.535 < $X_{F,O}$ < 0.65) and nozzle exit velocities (330 < U_O < 420 cm/s). Note that the nozzle exit velocites, in which BDSE is obersved, are much larger compared to those in the previous study that the nozzle exit velocities are much smaller than the stoichiometric flame speeds [6]. However, a different type of self-excitation in regime III appears near extinction limits at 0.28 < $X_{F,O}$ < 0.32 and U_O < 40 cm/s. To investigate the differnce between the self-excitation in regime III and the BDSE, variation of flame dimensions with time was also investigated in Fig. 7. The self-excitation frequency in the BDSE was 7.31 Hz. The flame tip height and the flame length in the case of BDSE in Fig. 5(a) are shown to be in phase, whereas the flame tip and base heights are out of phase. Such characteristics are same to BDSE in Fig. 3(a) and very similar to those for the BDSE observed in the previous studies [3]. However, for the self-excitation in regime III, the flame tip and base heights are in phase, while the heights and the flame length are out of phase. Also, note that the self-exciation frequencies in regime III are slightly smaller than those for BDSE, i.e. 5.47 Hz. These results are very similar to those observed just prior to flame extinction [5]. However, the LCB is not

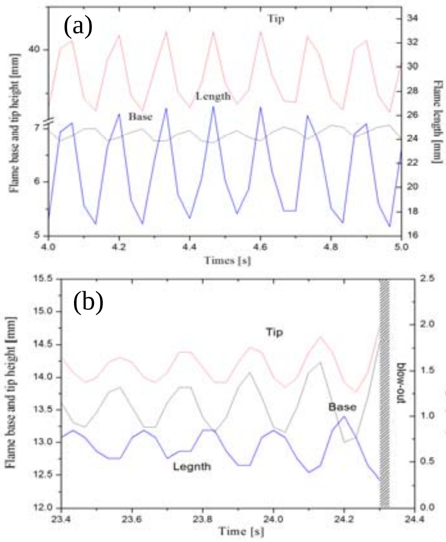

Figure 7. Various flame dimensions of self-excitation lifted flame for BDSE (a) at $X_{F,O}$ = 0.55, and U_O = 300 cm/s, and self-excitation in regime III (b) at $X_{F,O}$ = 0.28, and U_O = 30 cm/s for 10 % helium addition.

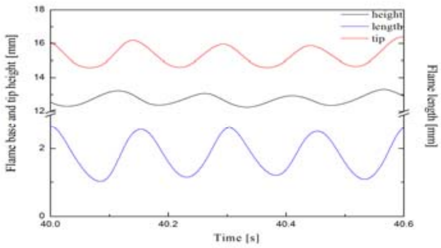

Figure 8. Various flame dimensions of self-excited lifted flame with LCB for D = 0.95 mm.

appeared by using fuel tube nozzle 0.95 mm in diameter. Considering that LCB appeared at more exccesive heat losses from flame to ambience, experiment with 25 % helium dilution was conducted, and showed LCB appeared at $X_{F,O}$ = 0.48, U_o = 60 cm/s, and V_{CO} = 8 cm/s . To analysis the behavior of the LCB, various flame dimensions were showed by diagram in Fig. 8. The phase of tip height was unmatched to base height (the phase between the heights to flame base and tip is not 180°), while flame length and flame tip height are in phase. These results are very similar to the results in Fig.3(b).

Further investigation may be requred to confirm the experimental evidence to the self-excitations in regime III, based on the previous studies [6, 9, 10] that critical Lewis number for Le-ISE can be redcued if heat is lost from flame, and the flame with excessive heat losses could be self-excited even at Lewis numbers less than unity. Figure 9 demonstrates flame stability maps in nitrogen-diluted methane jet flames (Lewis number less than unity) with helium-diluted (3 and 4 %) coflow air. The results show that self-excitations exist at 0.48 < $X_{F,O}$ < 0.50 for U_O < 50 cm/s in the case of 3 % helium addition to colflow air and at 0.48 < $X_{F,O}$ < 0.51 for U_O <80 cm/s in the case of 4 % helium addition. As shown in Fig. 10, the self-excitation in regime III for methane flame is very similar to that for propane (in Fig. 7(b)).

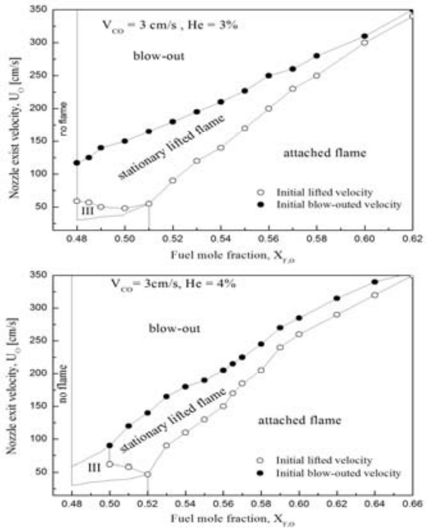

Figure 9. Flame stability map as a function of initial mole fraction for methane diluted with 3 and 4 % helium addition to coflow air for D = 0.95 mm and V_{CO} = 3 cm/s.

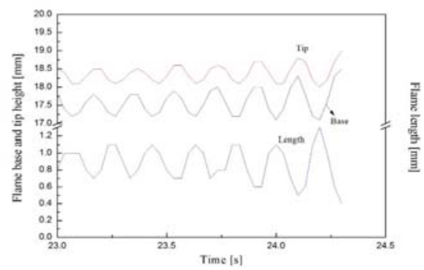

Figure 10. Various methane flame dimensions of lifted flame for self-excitation in regime III at $X_{F,O}$ = 0.50, U_O = 55 cm/s, and V_{CO} = 3 cm/s.

It is also noted that the regime III is extended in increase of helium mole fraction in the coflow air. Such phenomena are in consistent with the previous results [6, 9, 10] that the critical Lewis number for Le-ISE could be reduced and the Le-ISE could be thereby observed even at Lewis number less than unity. Consequently, it is assured that the self-excitation observed in the regime III is caused by Lewis number coupled with heat losses (thereby Le-ISE). However, further confirmation will be a future work through microgravity experiments.

Conclusion

Experiments in laminar lifted coflow-air propane and methane jet flames diluted highly with nitrogen were performed to investigate discernible differences between BDSE and Le-ISE as well as their interaction. It was shown that phase diagrams of flame dimensions for BDSE, LCB and Le-ISE were quite different, and recognized that the Le-ISE was mainly observed just prior to flame extinction at much lower Damkhöler numbers. In that self-excitation in regime III appeared near extinction limit in nitrogen-diluted propane or methane (Lewis number less than unity) jet flames, the Le-ISE observed in the present study is very similar to those of numerical results[6, 9, 10]. However, further sconfirmation will be a future work through microgravity experiments.

Acknowledgements

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 (2013 – 2014)

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