A Study on Self-excitations in Laminar Lifted Coflow-jet Flames

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1 Introduction

Laminar non-premixed lifted free- and coflow-jet flames, since the comprehensive study[1, 2], have been widely studied, because the fundamental characteristics are useful in extended laminar stretched flamelet modeling and also in designing industrial burners. 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. However, such lifted flames can be sometimes self-excited when the tribrachial flame velocity varies due to several factors such as Lewis number larger than unity, mixture strength, the repetitive interaction of burning rate and buoyancy-driven convection, buoyancy due to a flame flicker, and conductive heat loss from premixed wings to trailing diffusion flame.

Won et al investigated self-excitation with the frequency of the order of $O(1)$ Hz in laminar lifted coflow-jet flames, and concluded that this self-excitation was caused by buoyancy-driven self-excitation (hereafter, called BDSE) [3]. Meanwhile, Füri et al also studied self-excitation with similar orders in frequency in coflow-jet flames, and identified Lewis-number-induced self-excitation (hereafter, called Le-ISE) [4] just prior to flame extinction. Won et al extended thier work through normal- and micro-gravity experiments as well as numerical simulation, and verified that the self-excitations were caused by the repetitive interaction of burning rate and buoyancy-induced convection [5]. 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 dramatically 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

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evidently suppressed by the BDSE. 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. This was a sole experimental evidence to observe the Le-ISE in tribrachial flame. 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.

2 Experimental facility

Figure 1 shows the schematics of experimental setup and flow system in a coflow-jet burner configuration. The experimental facility consisted of a coflow-jet burner, mass flow controllers, 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 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 flow rates were controlled precisely by using mass flow controllers 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. The fuel nozzle tube length was more than 100 times the nozzle diameter to attain fully developed velocity profiles. 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. 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 points in converted gray-level images.

3 Results and discussion

Experiments were conducted to first confirm the existence of Le-ISE in laminar lifted jet flame configuration, and subsequently to investigate the difference between BDSE and Le-ISE as well as their interactions. Figure 2(a) shows flame stability map as a function of nozzle exit velocity U_O and fuel mole fraction $X_{F,O}$. The stability map, experimented with 9.4 mm nozzle diameter, shows that two types of self-excitation regime exist: BDSE (regime I), and Le-ISE coupled with BDSE (hereafter called LCB, regime II). The LCB was observed at very low $X_{F,O}$, such that self-excitations appeared just prior to flame extinction when fuel Lewis number was much larger than unity [4]. Figure 2(b) compares BDSE with LCB. Particulary in the case of LCB, 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 premi-

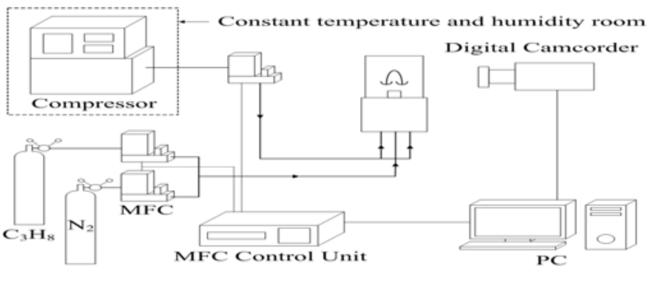

Figure 1. Schematic experimental setup and flow system about coflow-jet burner configuration.

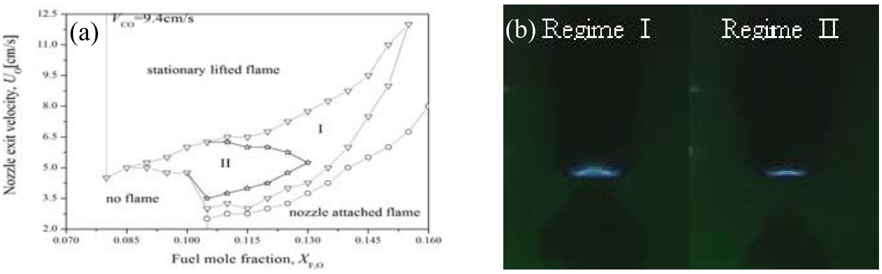

Figure 2. BDSE versus LCB: (a) flame stability map and (b) direct images of BDSE through Mie-scattering technic (I) at $X_{F,O}$ = 0.13, U_O = 7.25 cm/s, V_{CO} = 9.4 cm/s and (II) at $X_{F,O}$ = 0.1, U_O = 5c m/s, V_{CO} = 9.4 cm/s for 9.4mm nozzle diameter.

-xed wings to the trailing diffusion flame. Based on the previous results [10] that edge flame was self-excited due to excessive radiation heat loss near extinction Damköhler number, 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:

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

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. Figure 3 represents the functional dependency of Damköhler number on lifted-off height for various nozzle exit velocities; (a) BDSE at $X_{F,O}$ = 0.13 and (b) LCB at $X_{F,O}$ = 0.1. In cases of BDSE in Fig. 3(a), the shape is of a simply connected ellipse; the flame moves in the counterclockwise direction. In cases of LCB in Fig. 3(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 than those in BDSE). It is also noted that the conductive heat loss to trailing diffusion flame can be much significant in LCB as shown in Fig. 2(b) and the flame size is relatively small as well.

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. Resultamtly, 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. To control conductive heat losses from flame to ambience, experiments were conducted by adding helium to the outer coflow air. Figure 4 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 was 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 [5]. However, a different type of self-excitation in regime III appears near extinction lim-

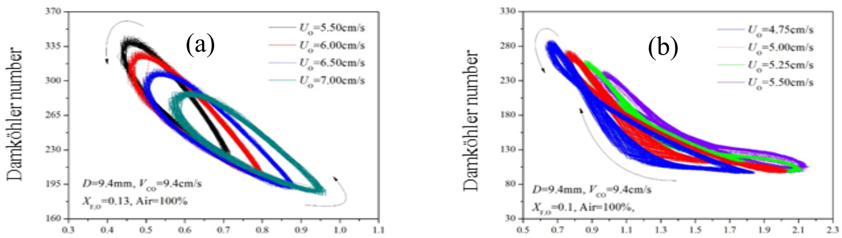

Figure 3. The functional dependency of Damköhler number on lift-off height for various nozzle exit velocities.

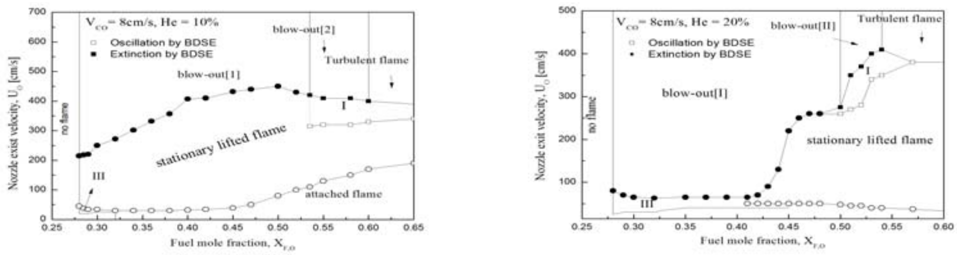

Figure 4. Flame stability maps for D = 0.95mm and Vco = 8cm/s.

-its at 0.28 < $X_{F,O}$ <0.32 and U_O < 40 cm/s.

To clarify the differnce between the self-excitation in regime III and the BDSE, variation of flame dimensions with time was investigated in Fig. 5. 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 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 [4]. The previous study [10] recognized that the self-excitation frequency for Le-ISE increased and then decreased with Damköhler number. Thus the self-excitation frequency with nozzle exit velocity was also investigated at various fuel mole fractions in Figure 6. Note that the self-excitation frequency for BDSE decreased monotonously with nozzle exit velocity at various fuel mole fractions in the previous study [5]. The results in Fig. 6 shows that the self-excitation frequency with nozzle exit velocity increases and then decreases. These results are rather well consistent with those of numerical results in the 2D mixing layer, confirming that the self-excitations are addressed to Le-ISE [9, 10]. Furthermore, the previous studies [6, 9, 10] noticed that critical Lewis number for Le-ISE can be redcued if heat is lost from flame, and also found that the flame with excessive heat losses could be self-excited even at Lewis numbers less than unity. Then, further investigation may be requred to verify them experimentally for the self-excitations in regime III. Figure 7 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. Even if we do not provide in detail, similar results to those in Fig. 5(b) and Fig. 6 are obtained. It is also noted that the regime III is extended in increase of helium mole fraction in the coflow air. Such a phenomena is in consitent 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.

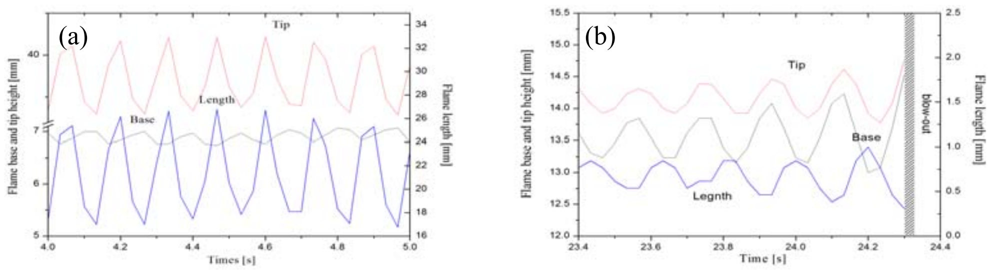

Figure 5. Various flame dimensions of self-excitation lifted flame about BDSE (a) at $X_{F,O}$ = 0.55, U_O = 300 cm/s and self-excitation in regime III (b) at $X_{F,O}$ = 0.28, U_O = 30 cm/s Helium-diluted for 10%

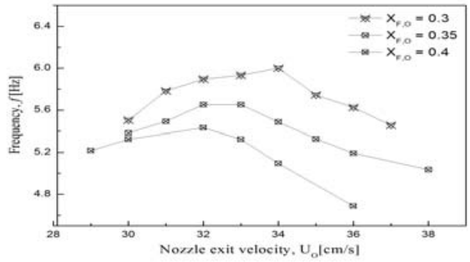

Figure 6. Variation of the frequency of self-excitation with nozzle exit velocity in regime III.

Now it may be required to characterize the self-excitation in regime III with a functional dependency of Strouhal number upon related physical parameters, and is shown in Fig. 8. The results show that the self-excitation in regime III is well described by a functional depency of Strouhal number on Lewis number, fuel mole fraction, and normalized nozzle exit velocity: The best fits are presented as follow eq. (2):

$$St_{LISE} = 0.001 \times \alpha^{0.65}$$

(with a correlation coefficient of 0.950) and

$$St_{LISE} = 0.1 \times \alpha^{-1.5}$$

(with a correlation coefficient of 0.945) (2)

where $\alpha = Le_F\, S_L^O / U_O X_{F,O}^{0.75}$. The stoichiometric laminar burnig velocity and nozzle exit velocity are related to the chemical time scale and diffusional time scale, repectively. Hence the nomalized velocity implies an effective Damkhöler number. Resultantly, the results are also consistent in the dependency of the self-excitation frequency of Le-ISE on Damkhöler number the previous results [10].

4 Conclusions

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 and Le-ISE are quite dif-

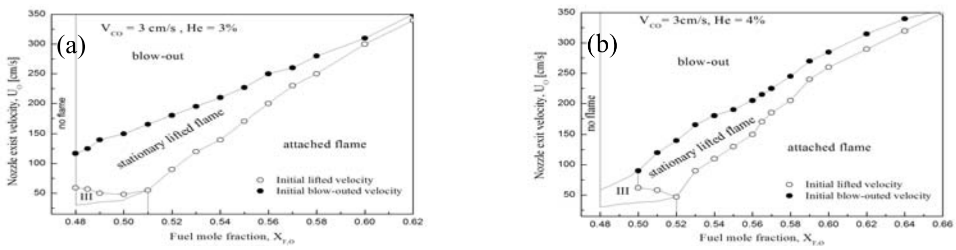

Figure 7. Flame stability maps with nozzle exit velocity as a function of initial mole fraction for Methane in helium-diluted with 3 and 4% to coflow side for D = 0.95 mm and Vco = 3cm/s.

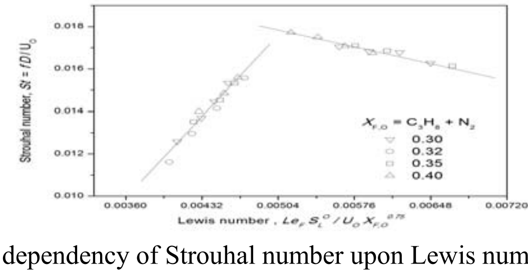

Figure 8. The functional dependency of Strouhal number upon Lewis number and normalized velocity.

-ferent, and recognized that the Le-ISE was mainly observed just prior to flame extinction at much lower Damkhöler numbers. The self-excitation with nozzle exit velocity increased and then decreased for Le-ISE, while it decreased monotonously for BDSE. In many aspects, the Le-ISE observed in the present study is very similar to those of numerical results in the 2D mixing layer [6, 9, 10]. However, further confirmation will be a future work through microgravity experiments.

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