

A study on Self-excitation in Laminar Lifted Propane Coflow-Jet Flames Diluted with Nitrogen

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1. Introduction

Lifted flames have been studied extensively to understand the fundamental characteristics of it and to design practical burners. Laminar lifted flames in free- and coflow-jet configurations have to be stabilized on a stoichiometric contour due to the intrinsic feature of tribrachial structure such that the tribrachial flame velocity is balanced to the local flow one. [1, 2] However, such lifted flames are occasionally destabilized in the case that the tribrachial flame velocity varies due to various factors such as Lewis number larger than unity [3-7], the repetitive interaction of burning rate and buoyancy-driven convection [8-9], buoyancy due to a flame flicker [10], and conductive heat loss from premixed wings to trailing diffusion flame. [11, 12]

Won et al. [8] and Furi et al. [6] investigated self-excitations with the similar frequency of $O(1)$ Hz in laminar lifted coflow-jet flames, and identified as Lewis-number-induced and buoyancy-driven self-excitations, respectively. The extended work through the comparison between normal- and micro-gravity experiments [9] verified that the self-excitations were caused by the repetitive interaction of burning rate and buoyancy-induced convection (i.e. buoyancy-driven self-excitation), thereby having been believed to preclude all doubts since that. Then, two possible scenarios can be made in laminar lifted jet flame: laminar lifted jet flame cannot be self-excited by Lewis number even much larger than unity and/or Lewis-number-induced self-excitation (hereafter called Le-ISE) can be significantly suppressed by buoyancy-driven self-excitation (hereafter called BDSE) or another. However, note that Le-ISE has been well identified numerically in various edge flame configurations such as two-dimensional mixing layers [3-5] and two-dimensional counterflow flame [13]. The results showed that edge flame underwent self-excitation for sufficiently small Damkohler numbers (near extinction) and Lewis numbers sufficiently larger than unity as well as that even

smaller than unity in case of edge flame experiencing excessive heat losses. Then, further experimental trials may be required to find the existence of Le-ISE in laminar lifted jet flame.

In the current study experiments were conducted to first confirm existence of the Le-ISE experimentally in laminar lifted jet flame configuration and subsequently to investigate the difference between BDSE and Le-ISE and their interaction. The Le-ISE was produced at sufficient high nozzle exit velocities based on the background that Le-ISE was numerically observed almost at low Damkohler number [3-5]. Each distinct difference between BDSE and Le-ISE is compared and discussed.

2 Experimental setup and methods

The experimental apparatus consisted of a coflow burner, a flow control system, and the visualization setup. The fuel tube nozzle was 9.4mm in diameter and 100cm in length such that the internal flow can be fully developed. The tip of the fuel nozzle protruded 10mm over the honeycomb. The fuel used was chemically pure grade propane (99.95%) diluted with nitrogen. A nitrogen-diluted propane jet, controlled by mass flow controllers with maximum flow capacities of 10, 20, 30, 50, 200, 500, and 1000 ml/min, was injected through fuel tube nozzle. To minimize outside disturbances, an acrylic cylinder with 40 cm in length and 100 mm in inner diameter surrounded the coflow air. Coflow air was supplied to a coaxial nozzle through glass beads and ceramic honeycomb for flow uniformity. Compressed air whose humidity (41~43%) and temperature (23°C) were controlled in a constant temperature, humidity room was also used to eliminate the uncertainty due to ambient condition. A digital camcorder with the framing rate of 1/60 s (Sony, HDR-CX560) was used to capture direct flame images. The lift-off height, defined as the brightest point of the flame front from gray-level images (converted from color levels), was measured from the fuel nozzle exit with a cathetometer and the digital camcorder. A Matlab-based code was used to analyze flame images recorded over 80 s. FFT analyses for temporal lift-off height signal were made to determine distinct regimes in flame stability map. A two-dimensional traverse system was also used to obtain clear flame images.

3 Results and discussion

Stability map

Experiments in propane jet flames diluted with nitrogen were performed by varying fuel nozzle exit velocity U_O , initial fuel mole fraction $X_{F,O}$ and coflow velocity V_{CO} was fixed at 9.4cm/s. Fig. 1 shows flame stability map as functions of U_O and $X_{F,O}$ with $D = 0.94$ cm. At $X_{F,O} < 0.1$ and/or for $U_O < 5.0$ cm/s at $0.1 \leq X_{F,O} \leq 0.105$, the flame was not ignitable. At $X_{F,O} > 0.135$, only the BDSE was observed. The experiments was concentrated on the range of $0.1 \leq X_{F,O} \leq 0.135$ since the Le-ISE appeared in the range and the aim in the current study was to distinguish Le-ISE from BDSE as well. Flame blowout was out of our interest, thus it was also excluded in the stability map.

Two types of self-excited flame were observed: (I) BDSE and (II) (I) + Le-ISE. The BDSE existed at $X_{F,O} \geq 0.1$; a coupled form of Le-ISE and BDSE appeared at $0.1 \leq X_{F,O} \leq 0.13$. Similarly to those in the previous studies [8, 9], the nozzle exit velocities were much less than the stoichiometric laminar flame speeds in ranges of 20.6-26.0 cm/s at $0.1 \leq X_{F,O} \leq 0.135$ and were also smaller than the coflow air velocity. In this situation, the BDSE could appear due to the repetitive interaction of burning rate and buoyancy-induced convection [8, 9]. As shall be shown later, in the regime I, the Le-ISE was launched while the BDSE disappeared, and vice versa.

Meanwhile the more nitrogen mole fraction increased, the more pronounced Le-ISE became. Furthermore, the Le-ISE arose when fuel mole fraction was relatively further highly diluted. In creasing 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 Damköhler number decreased in the previous numerical simulations [5]. Additionally,

note that the fuel Lewis numbers are larger than 1.85 in the regime II, thereby being susceptible for Le-ISE.

The BDSE

The mechanism of BDSE has been identified in the past studies [8, 9]. At a downstream location, the flame tends to advance upstream since the stoichiometric burning speed is much larger than the local flow velocity. The partially premixed mixture is accumulated gradually in front of edge flame and thereby the mass flux into the flame increases while the flame migrates upstream, therefore leading to increase in flame length and burning rate, and intensifying buoyancy force as well. Subsequently this can lead to the increase in axial flow velocity. As the local flow velocity exceeds the edge propagation speed, the flame will migrate downstream again. This repetitive nature is mechanism of BDSE.

The various dimensional features of BDSE at $X_{F,O}=0.13$, $U_0=7.25\text{cm/s}$ and $V_{CO}=9.4\text{cm/s}$ are demonstrated in Fig. 2 (a). The heights to flame base and tip as well as the flame width are shown during one cycle of the self-excitation with a frequency of 2.23 Hz. The results show that the phase difference between the heights to flame base and tip is 180° , thereby repeating the extension and contraction in flame length. To further clarify the feature, the phase diagram was plotted in Fig. 2(b). The Flame length became short during the falling period corresponding to the flame base migrating upstream. Furthermore, the variation rates of flame length during the falling and rising periods are almost similar. As the flame base height approached its minimum, the flame length increased again. After reaching a maximum flame tip height, the flame length decreased again. The self-excitation was repeated in such a manner. Consequently, the buoyancy is pronounced such that the burning intensity can increase due to entrained fuel flux when the flame migrates upstream. Meanwhile, when flame migrates downstream, buoyancy decreases due to contraction of the flame.

The Le-ISE coupled with BDSE (LCB)

The mechanism of the Le-ISE is needed to be identified physically, in that the Le-ISE has not been so far found experimentally in laminar lifted flame and thus the mechanism of it has not been clarified. The features for a coupled form of Le-ISE and BDSE(hereafter called LCB) with the frequency of 2.92 Hz at $X_{F,O}=0.1$, $U_0=5\text{cm/s}$ and $V_{CO}=9.4\text{cm/s}$ are shown in Fig. 3. The phase difference between the heights of tip and base is not 180° . Additionally, there exists a basin in flame length and width such that they does not change so much. Therefore, the behavior of LCB is seen to be quite different from that of BDSE. The phase diagram of flame length versus lift-off height is also presented in Fig. 3(b). Variation rate of the flame length during falling period is quite different from that during rising period. That is, the flame length first changes mildly and then varies precipitously around the minimal lift-off height during rising period. For better understanding, direct sequential images for BDSE and LCB are compared in Fig. 4. As shown in Fig. 4 the BDSE the heights of base and tip are repeatedly extended and contracted. Meanwhile, the flame length in the LCB during falling and rising periods indicates an asymmetric aspect. The flame volume is very small during the falling period, meaning that buoyancy effect is relatively small and thereby the flame can be susceptible to Le-ISE due to Lewis number much larger than unity. In this situation, the flame shape of lifted flame is very similar to premixed-like flame which can be observed near flame blowout. In such a case, conductive heat loss from premixed wings to trailing diffusion flame can be significant [11, 12]. This can reduce a critical Lewis number for Le-ISE [5]. Furthermore the effective Damköhler number can be defined as $Da = \frac{\tau_d}{\tau_c} = \frac{w/U^*}{\delta_{ft}/S_L|_{st}}$. The effective Damköhler number becomes small near the maximum lift-off height since the flame width is appreciably small, thereby being susceptible to Le-ISE [5]. Meanwhile, the tiny lifted flame did not lead to extinction but advanced upstream; In this case the fuel concentration gradient could be small and the partially premixed mixture in front of edge flame could be preheated due to fuel Lewis number much larger than unity; this caused edge flame speed to increase and thereby the flame migrated upstream. Fig. 4 also

showed that the flame volume upstream increased appreciably. Then buoyancy effect becomes significant, increasing the buoyancy-induced convection speed; furthermore the local flow speed at the upstream can be larger; then the flame migrates downstream. Furthermore, appreciable increase in flame width upstream can also increase the effective Damköhler number. In this situation, it can be very hard for Le-ISE to be encountered. This repetitive nature can be the mechanism of LCB.

To further clarify the difference between BDSE and LCB, the functional dependency of lift-off height on the effective Damköhler number was plotted in Fig. 5. Here $\delta_{f,t}$ denotes the flame thickness and $S_L^*|_{st}$, w , and U^* represent the stoichiometric laminar burning velocity, the flame width, and the local flow velocity at the tribrachial point, respectively. The flame properties were calculated using the USC Mech. II [14]. The local flow velocity was calculated using the jet similarity theory which is proposed by Lee[1]. In Fig. 5a the BDSE with an oval-like shape shifts merely in increase of nozzle exit velocity without changing its shape. The motional direction was counterclockwise. However the LCB has a twisted shape. In the LCB, the Le-ISE appeared at low effective Damköhler number and its motional direction was clockwise; the BDSE arose at high effective Damköhler number and its motional direction was restored to be counterclockwise again. Our study is still ongoing to completely distinguish Le-ISE from BDSE and also to characterize the Le-ISE.

4 Conclusions

Experiments in highly nitrogen-diluted laminar lifted propane coflow jet flame were performed to investigate the difference between BDSE and Le-ISE and thier interaction. The Le-ISE was launched at low effective Damköhler number and large lift-off height. Such a lifted flame with a premixed-like flame shape was so tiny that buoyancy force could be small. In such a flame shape conductive heat loss from premixed wings to trailing diffusion flame could be significant. This could reduce the effective Damköhler number, thereby being susceptible to Le-ISE. However, there remains to characterize the Le-ISE in the future.

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6 Figures

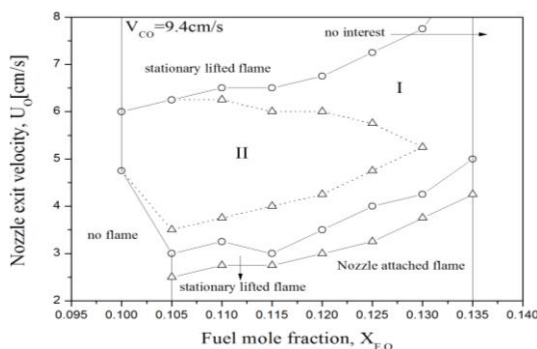


Fig. 1 Flame stability map as functions of the nozzle exit velocity and initial fuel mole fraction for $D=0.94$ cm and $V_{CO}=9.4$ cm/s.

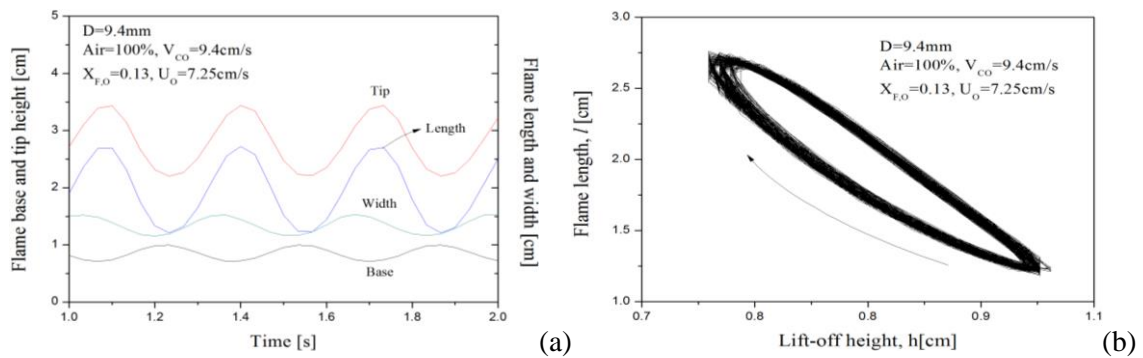


Fig. 2 Features in BDSE; (a) various flame dimensions of BDSE and (b) phase diagram of lift-off height versus flame length at $X_{F,O}=0.13$, $U_O=7.25$ cm/s, and $V_{CO}=9.4$ cm/s.

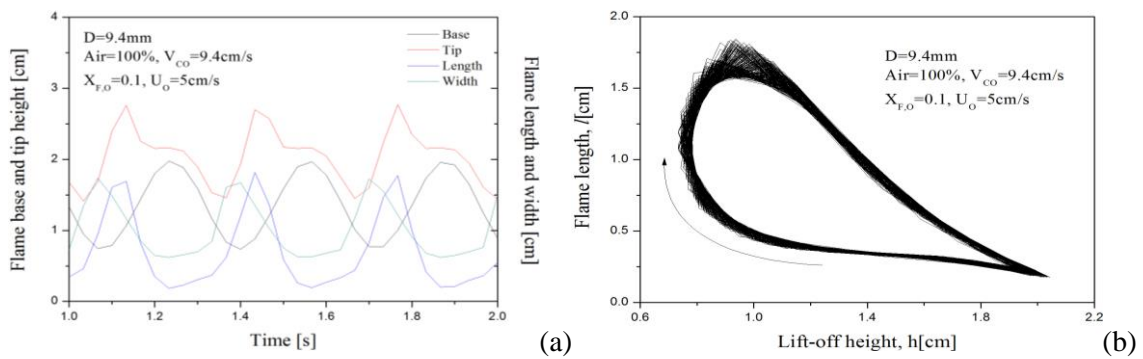


Fig. 3 Features in LCB; (a) various flame dimensions of LCB and (b) phase diagram of lift-off height versus flame length at $X_{F,O}=0.1$, $U_O=5$ cm/s, and $V_{CO}=9.4$ cm/s.

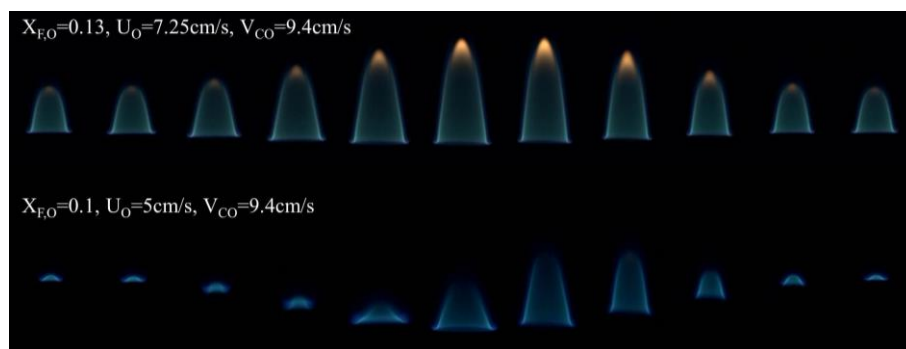


Fig. 4 Comparison of BDSE (the upper images) with LCB (the lower images). They were displayed with time step of 0.033 s in a one cycle.

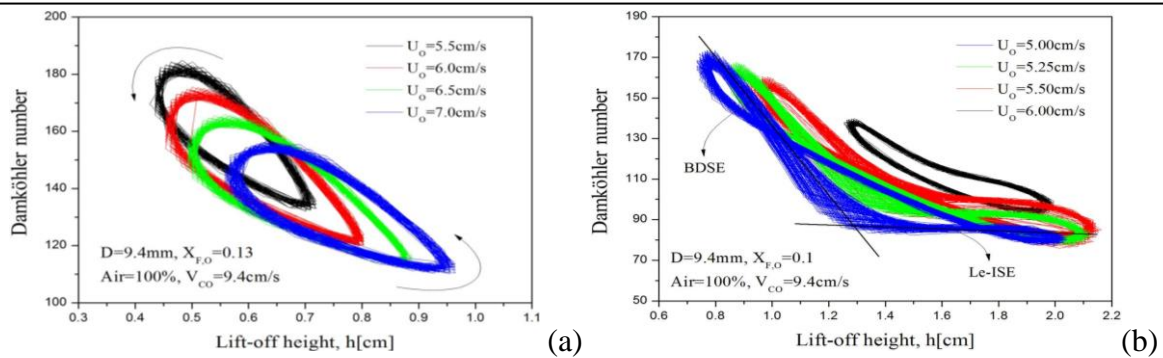


Fig. 5 The Functional dependency of Damköhler number on lift-off height for various nozzle exit velocities; (a) BDSE at $X_{F,O}=0.13$ and (b) LCB at $X_{F,O}=0.1$.

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