A Study on Diffusive-Thermal and Buoyancy-driven Instabilities in Laminar Free-jet Flames with applied DC electric fields

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Abstract

Self-excitations in horizontally and vertically injected laminar free-jet flames with applied DC electric fields are experimentally investigated and distinctly classified into three: a buoyancy-induced self-excitation due to a flame flicker, a Lewis-number-induced self-excitation, and the fundamental mode as well as their overtones of a derived buoyancy-induced self-excitation. The application of DC electric fields to jet flames was experimentally designed to suppress heat-loss-induced self-excitations to highlight the definite difference between Lewis-number-induced self-excitation and the derived buoyancy-induced self-excitation with the same order of 1 Hz. The current study presents the distinct regimes of those distinct self-excitation modes in the flame stability maps for vertically and horizontally injected jet flames. The results show that the buoyancy-induced self-excitation with *O*(10) Hz due to a flame flicker causes the frequencies of the fundamental mode with *O*(1) Hz as well as their overtones of a derived buoyancy-induced self-excitation. Once the buoyancy-induced self-excitation with *O*(1) Hz is derived, the mode suppresses Lewis-number-induced self-excitation. The characteristics between the Lewis-number-induced and the derived buoyancy-induced self-excitation are compared and discussed in detail. The individual phase diagrams in the distinct regimes are presented, and thereby the individual key feature for the above-mentioned self-excitations is also highlighted.

Introduction

Much research efforts have successfully devoted to grasp the buoyancy-driven self-excitation [1, 2], the diffusive-thermal instability with large initial mixture strengths in near extinction [3], the heat-loss-induced self-excitation [4] and the oscillation prior to extinction of condensed-phase fuels [5]. Especially, Won et al. [1] and Füri et al. [3] made the different explanations for the similar self-exciations in the similar coflow jet configurations. Since that, Won et al. [2] concluded that, from the comparison between normal- and micro-gravity experiments, the self-excitations were caused by buoyancy effect, thereby having been believed to preclude all doubts. Additionally, Kurdyumov and Matalon [6-8] demonstrated that the self-excitations at near the tip of the splitter plate could be attributed to excessive volumetric heat-loss and low Damköhler number. However, despite their extended buoyancy-free numerical simulations within the context of diffusive-thermal instability, the experimental evidences have not been so far found in the literature.

Recently, Yoon et al. [4] also observed the similar self-excitations with the similar frequency ranges in laminar lifted free-jet flames, concluding that the self-excitation could be also caused by buoyancy from the fact that the self-excitations disappeared in a horizontally injected laminar lifted nitrogen-diluted propane flames at the same flame conditions. However, they also showed that heat-loss-induced self-excitation suppressed the buoyancy-induced self-excitation. Then, one infers that there can be such possibilities that heat-loss-induced as well as buoyancy-induced self-excitation can strongly suppress Lewis-number-induced self-excitation. The current study was motivated by these arisen possibilities, and the experiments were designed to distinguish Lewis-number-induced self-excitation from buoyancy-induced self-excitation and also to find the two different behaviors in terms of related physical parameters.

Electric fields could alter various combustion characteristics through the acceleration of charged particles by the Lorentz force. This acceleration could lead to the drift velocity and the increase in kinetic energy such that the mobility and chemical reaction associated with charged particles can be enhanced [9]. Recently, a single electrode configuration has been proposed on studying the stabilization of turbulent jet flames [10], where the single electrode is interacting with charged particles existed in a flame zone, in much the same way as between a lightening rod and clouds. The single electrode configuration with the AC frequency range of 60 – 1500 Hz has been successfully applied in the studies of the stabilization of jet flames, including the characteristics of liftoff and reattachment [10-12]. In this respect providing electric fields, it is offered to control Damköhler number in identical environment that flame has same flow velocity, proportion fuel and diluents.

The application of electric fields to jet flames can have several advantages for our designed experiments. That is, the drastically extended critical lift-off velocity can permit the jet flames to be attached to the nozzle exit, and this can essentially suppress the heat-loss-induced self-excitation from premixed wings to the trailing diffusion flame in much wider ranges since the edge flame shape is of diffusion flame extinction [4]. Furthermore, a methane jet even with Schmidt number less than unity can be lifted in a stationary manner near the nozzle exit. Then, under the application of DC electric fields to jet flames, the selection of mixture fuels with large Lewis numbers can force the jet flames to be susceptible to Lewis-number-induced self-excitations; meanwhile that with small Lewis numbers be more sensitive to buoyancy-induced self-excitations. In the present work, experiments were designed to clearly compare Lewis-number-induced and buoyancy-driven self-excitations in laminar free-jet flames with DC electric fields. Two types of configurations with the horizontal and vertical fuel injections were used for the designed experiments under the low Damköhler number using DC electric fields. The detailed discussions about the observed results are focused on the differences between Lewis-number-induced self-excitation and buoyancy-induced self-excitation.

Experiment

The experimental apparatus consisted of a free-jet burner, mass flow controllers, a DC electric field supply system, and a visualization system as schematically shown in Fig. 1. The fuel nozzle was made of copper with i.d. 0.55mm and o.d. 2.15mm. Fuel tube with the length of 85 mm was used to obtain fully developed velocity profiles. The free-jet jig was mounted inside an acrylic compartment (55cm x 50cm x 80cm), and a series of fine mesh screens were installed in lower and upper halves of the compartment to suppress external disturbances. A fined mesh made of accetal resign at the low part was used for electric insulation; meanwhile a fine steel mesh was installed at the upper part to present much stronger DC electric fields that than using a building ground.

Chemically pure grade of butane, methane, and diluents (nitrogen and helieum) with the purity of 99.95% were used. The flow rates of the fuels and diluents were controlled by mass flow controllers calibrated with wet-test gas meters. The applied voltage was fixed to -10 kV in r.m.s. value. The applied voltage was monitored by an oscilloscope (Tektronix, TDS1001B) and a 1000:1 probe (Tektronix, P6015A). The quenching distance was measured

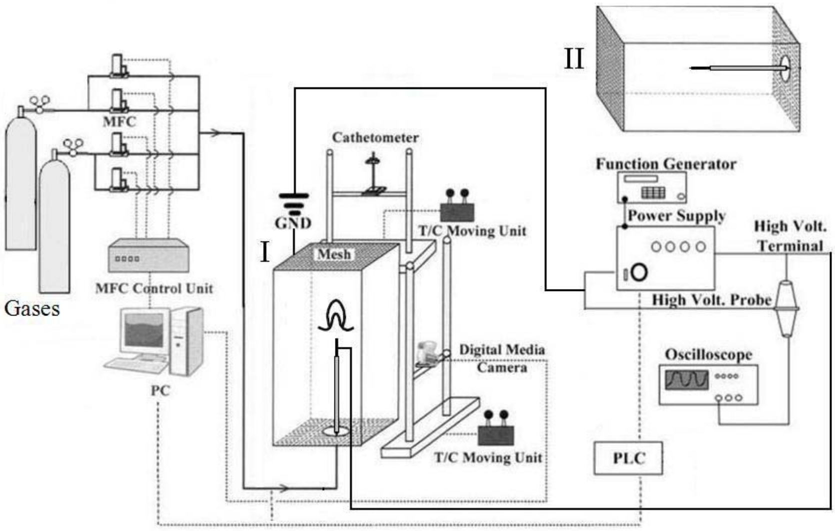

Figure 1 Schematic of experimental setup: (I) vertical and (II) horizontal injections.

with a cathetometer and a digital camera (Sony, HDR-SR11). A Matlab-based code was used to analyze flame images recorded over 137 s. The quenching distance was defined as the brightest point of the flame front from gray-level images (converted from color levels). A two-dimensional traverse system was also used to obtain clear flame images.

Results and discussion

Horizontally injected jet flames

The experiments in horizontally injected methane and butane jet flames diluted with nitrogen and helium were performed by varying the nozzle exit velocity U_0 and initial fuel mole fraction $X_{F,0}$ to minimize the buoyancy-induced self-excitation of edge flame. Figure 2 shows flame stability maps as functions of U_0 and $X_{F,0}$ in the horizontally injected fuel jets of (a) $CH_4 + N_2$, (b) $CH_4 + He$, (c) $C_4H_{10} + N_2$ and (d) $C_4H_{10} + He$. Five types of flame oscillations were observed: (I) buoyancy-induced self-excitation, (II) Lewis-number-induced self-excitation, (III) I + buoyancy-driven self-excitation, (IV) I + II and (IV) I + II + III. Each regime was divided into five regimes based on FFT analyses and their behaviors. As mentioned before, lifted flames were excluded to get rid of the possibility that heat-loss-induced self-excitations can affect the other self-excitations. Note that repetitive nature of burning rate and buoyancy-driven convection at triple point led to the buoyancy-driven self-excitation with the order of 1 Hz [1, 2]. On the other hand, the buoyancy-induced self-excitation with the order of 10 Hz can be regarded as that of a flame flicker.

As shown in Fig. 2, in all cases, buoyancy-induced as well as buoyancy-driven self-excitations were not observed because the horizontal injection suppressed buoyancy. For methane flames diluted with nitrogen in Fig. 2a, even a certain self-excitation does not appear because of Lewis numbers less than unity. The results also show that the attached flames are directly blown off when the nozzle exit velocity increases. For methane flames diluted with helium in Fig. 2b, particularly at $X_{F,0}$ <0.7 with Lewis numbers larger than unity, Lewis-number-induced self-excitation was not in attached flames; meanwhile, in lifted flames adjacent to the nozzle exit, Lewis-number-induced self-excitations appeared at relatively large $X_{F,0}$ such that heat-loss-induced self-excitation is less significant. Figure 3a demonstrates that, in lifted methane flame diluted with helium, the Lewis-number-induced self-excitations is intermittently included in the signal of lift-off height mainly caused by heat-loss-induced self-excitation (<0.1Hz) [4], even if those intermittent self-excitation frequencies cannot be

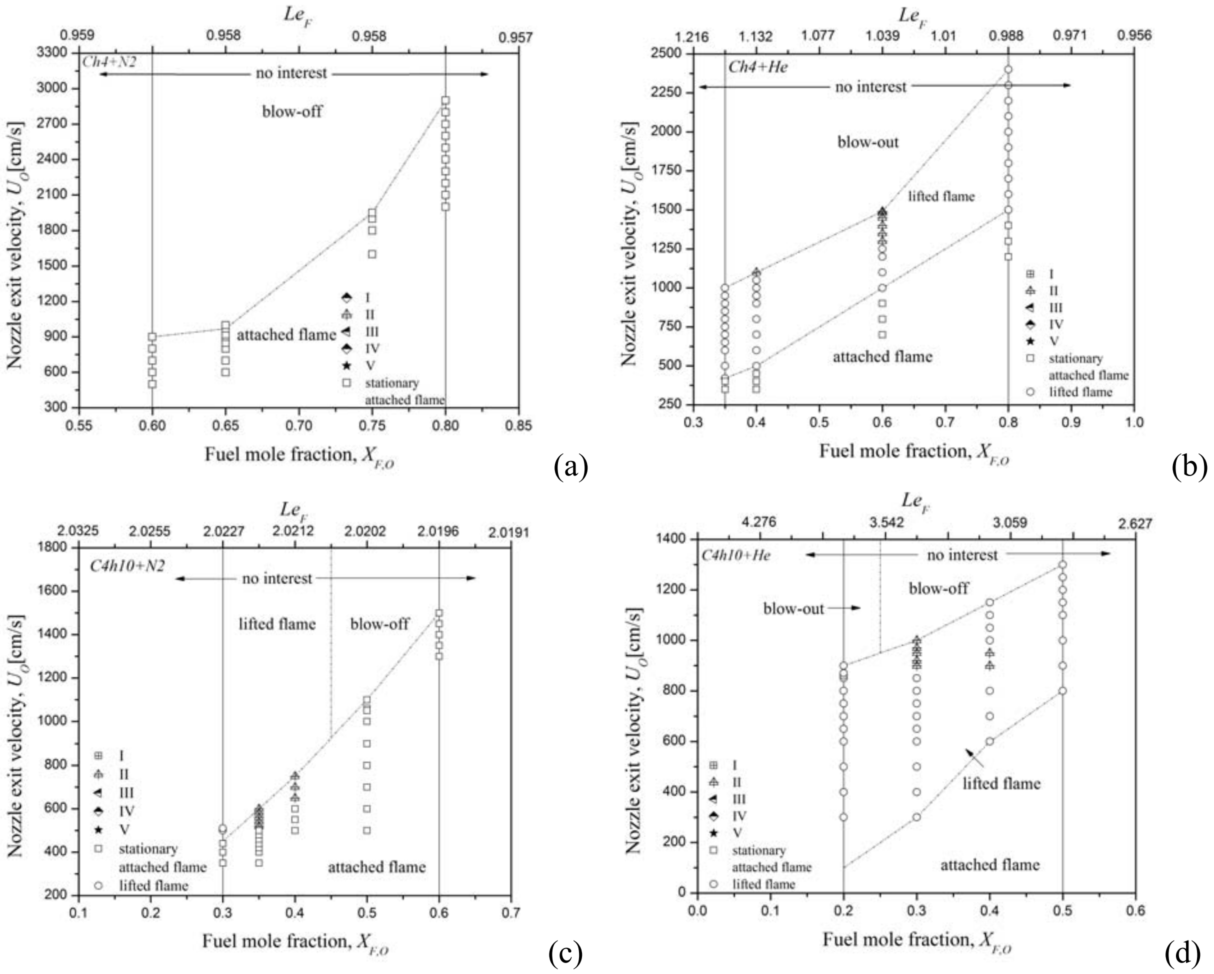

Figure 2 Flame stability maps as a function of nozzle exit velocity and initial fuel mole fraction in horizontally injected jets with (a) CH_4+N_2, (b) CH_4+He, (c) C_4H_{10}+N_2, and (d) C_4H_{10}+He.

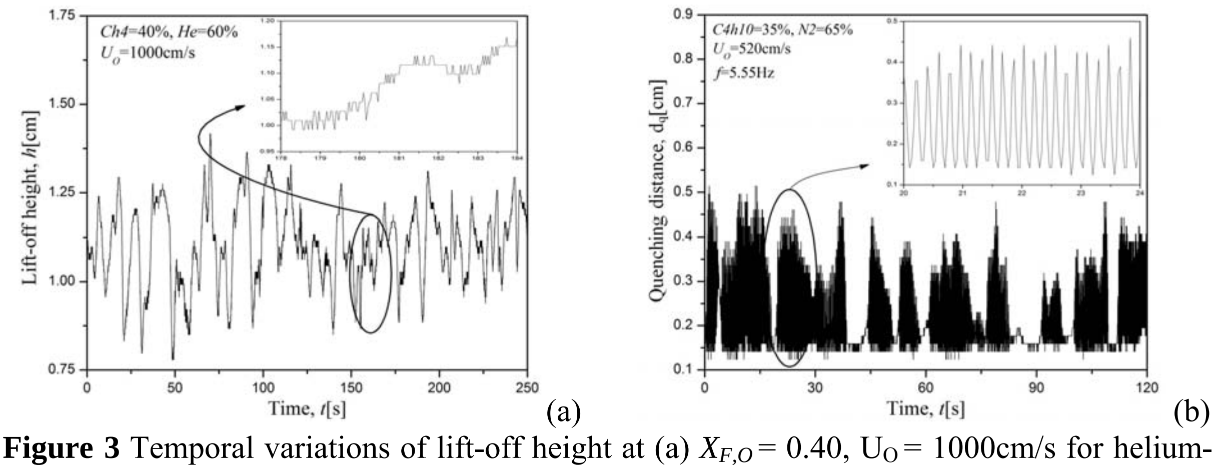

Figure 3 Temporal variations of lift-off height at (a) $X_{F,O}$ = 0.40, U_O = 1000cm/s for helium-diluted lifted methane jet flame and (b) $X_{F,O}$ = 0.35, U_O = 520cm/s in nitrogen-diluted lifted butane jet flame.

detected by FFT analysis. This implies that the heat-loss-induced self-excitation also suppresses Lewis-number-induced self-excitation.

The flame stability map in butane jet flames diluted with nitrogen in Fig. 2c shows that, at $X_{F,0}$ = 0.35 and 0.40 (Le>2.0), the attached flames oscillates due to diffusive-thermal instability. Also, Figure 3b demonstrates the typically temporal variation of quenching distance at $X_{F,0} = 0.35$, U_0 = 520 cm/s in nitrogen-diluted butane jet flames, corresponding tothe regime II. The obtained frequencies were in the range of 2.433 – 5.552 Hz at those flame conditions. However, note that, at $X_{F,0} \geq 0.5$, the Lewis-number-induced self-excitations were not also observed. At $X_{F,0} \geq 0.5$, an excessive soot forms on the rich premixed flame branch, and this restricts the Lewis-number-induced self-excitation due to the additional radiative heat-loss in rich premixed wings as well as the conductive heat loss from premixed flame branch to the trailing diffusion flame. At $X_{F,0}$ = 0.30, the Lewis-number-induced self-excitation did not appear in attached flames. When the nozzle exit velocity increases, the jet flame was lifted and was subsequently self-excited by heat-loss (<0.1 Hz), thereby also holding down the Lewis-number-induced self-excitation. For butane flames diluted with helium in Fig. 2d, even if the Lewis numbers for helium-diluted butane jet flames are larger than those for nitrogen-diluted butane jet flames, Lewis-number-induced self excitation also did not appear in attached flames. This can be attributed to the thermal conductivity of helium in comparison to that of nitrogen, reducing the reaction rate of edge flame and thereby edge flame speed. This is confirmed that, at $X_{F,0}$ = 0.80, the nitrogen-diluted jet flame is lifted at the nozzle exit velocity of 2900 cm/s; meanwhile the helium-diluted jet flame is lifted at the nozzle exit velocity of 1500 cm/s, thereby implying that much higher DC voltage can be required to attach the helium-diluted jet flame to observe the Lewis-number-induced self-excitation in attached flames. Furthermore, at $X_{F,0}$ = 0.40, the Lewis-number-induced self-excitation is observed at U_O =650-700 cm/s in nitrogen-diluted butane attached flames; meanwhile the nitrogen-diluted butane attached flame is already lifted at U_O=600 cm/s. This implies that a low Damköhler number can be the important factor for the occurrence of Lewis-number-induced self-excitation even if the Lewis-number-induced self-excitation depends upon Lewis number itself [6-8].

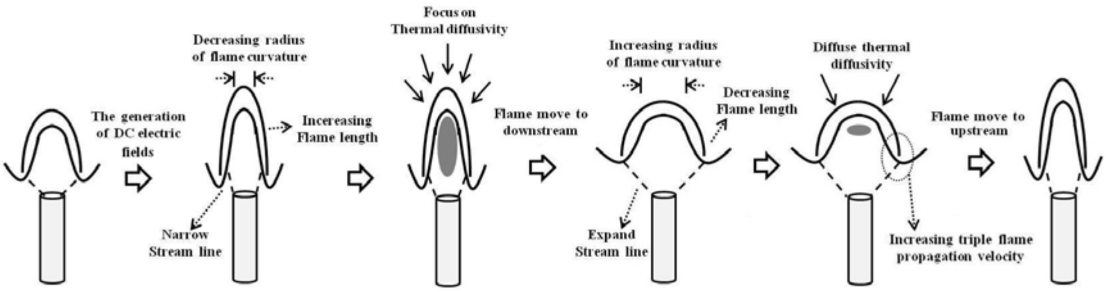

Figure 4 Mechanism of diffusive-thermal instability in laminar jet flames.

With the background of the experimental observations, the mechanism of Lewis-number-induced self-excitation can be explained. Fig. 4 illustrates the mechanism of the diffusive-thermal instability. The applied DC electric field significantly increases the edge flame speed, this makes the edge flame be more attached to the nozzle exit, the jet flame can be stretched and lengthy, and the radii of curvature of edge flame and near the tip of rich premixed wings can be reduced. Then, the thermal diffusion is concentrated near the tip of rich premixed wings, leading to the migration of premixed wing to an upstream location due to the enhanced propagation speed. The migrated edge flame to the upstream location encounters the correspondingly assigned, increased fuel concentration gradient at the triple point and furthermore the diffusive supply of reactant masses can be restricted due to the Lewis numbers much larger than unity. Then the edge flame tends to migrate downstream. During the half stroke of the self-excitation, these natures forces the tip part of rich premixed wings to advance upstream and the edge flame to recede downstream. Again, the receded edge flame

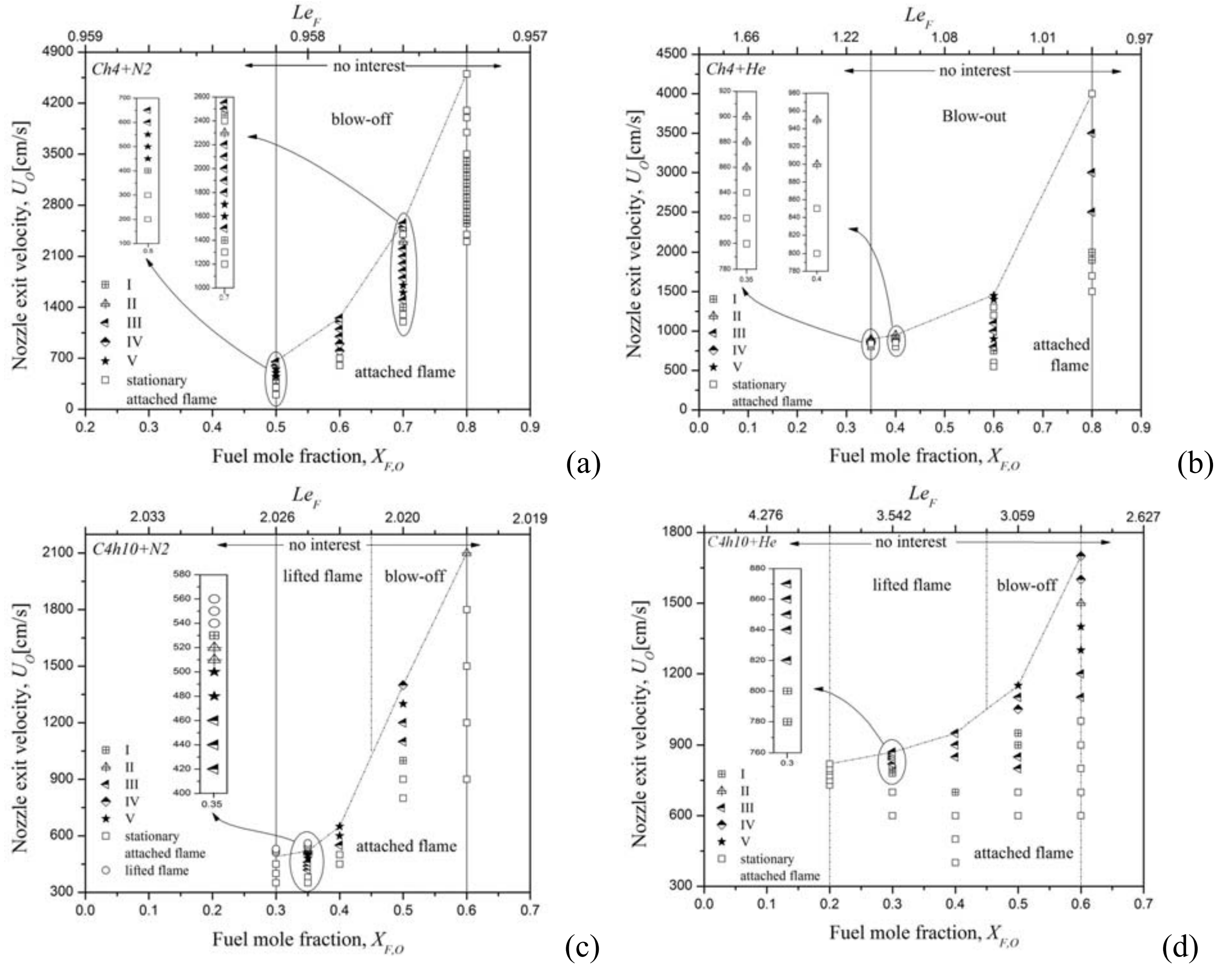

Figure 5 Flame stability maps as a function of nozzle exit velocity and initial fuel mole fraction in vertically injected jet flames with (a) CH_4+N_2, (b) CH_4+He, (c) C4H_{10}+N_2 and (d) C_4H_{10}+He .

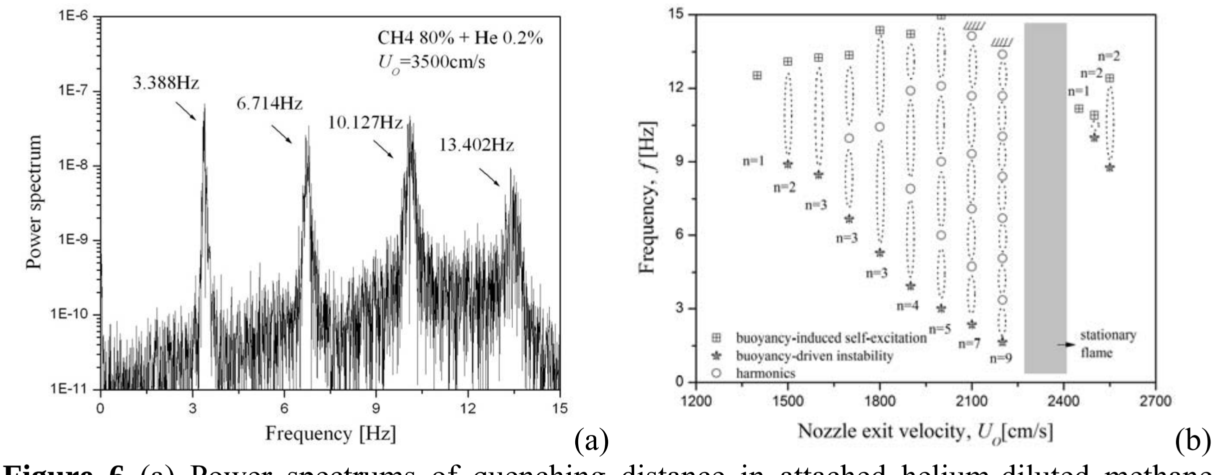

Figure 6 (a) Power spectrums of quenching distance in attached helium-diluted methane flame and (b) Representative genealogy of harmonic frequencies in buoyancy-induced self-excitations with the frequencies of the order of 1 Hz caused by buoyancy-induced self-excitation with the frequency of the order of 10 Hz at $X_{F,O}$=0.7 in nitrogen-diluted methane jet flames.

encounters the correspondingly assigned, reduced fuel concentration gradient at the triple point and furthermore the applied DC electric fields also increase the edge flame speed, thus advancing the edge flame upstream again. This nature can be the mechanism of Lewis-number-induced self-excitation. Then further definite evidences for Lewis-number-induced self-excitation may be required to investigate the coupled forms of Lewis-number-induced and buoyancy-induced self-excitations in vertically injected jet flames.

Vertically injected jet flames

To show Lewis-number-induced self-excitations more clearly, we conducted additional experiments in vertically injected jet flames. Figure 5 shows flame stability maps as the function of U_0 and $X_{F,0}$ in vertically injected jet flames with the fuels of (a) CH_4 + N_2, (b) CH_4 + He, (c) C_4H_{10} + N_2 and (d) C_4H_{10} + He. Compared to horizontally injected jet flames, buoyancy effects are pronounced, and thereby both the buoyancy-induced self-excitation with low and high frequencies appears, respectively. To clearly distinguish Lewis-number-induced self-excitation from both the buoyancy-induced self-excitation with low and high frequencies, we conducted FFT analyses in the regimes II and III for helium-diluted methane jet flames in Fig. 6. It is inferred that, because of Lewis numbers around unity in such for helium-diluted methane jet flames, Lewis-number-induced self-excitations can be less frequently encountered. Definitely, the 13.402 Hz can be attributed to a flame flicker due to buoyancy. In Fig. 6a, the frequencies of 3.388, 6.714, 10.172, and 13.402 Hz can be harmonic, thereby implying that the buoyancy-induced self-excitations with the low and high frequencies are closely correlated each other. At $X_{F,O}$=0.7, as shown in Fig. 5a, buoyancy-induced self-excitations with the frequencies of the order of 1 Hz are continuously found when nozzle exit velocity increases. At U_O=2300 cm/s, only a Lewis-number-induced self-excitation appears and then at U_O=2350 cm/s, the lifted jet flame becomes stationary. A buoyancy-induced self-excitation with the frequency of the order of 10 Hz appears at U_O=2400 cm/s, and then the buoyancy-induced self-excitation with the frequency of the order of 1 Hz at U_O=2500 cm/s is re-appears. In reality, this phenomenon is observed similarly in almost all cases, thereby implying that a close relationship between buoyancy-induced self-excitation with the high frequency and those with the harmonic frequencies can exist. In this regard, further exploration may be required to clarify this specific genealogy.

Fig. 6 demonstrates the representative genealogy of harmonic frequencies in buoyancy-induced self-excitations with the frequencies of the order of 1 Hz caused by buoyancy-induced self-excitation with the frequency of the order of 10 Hz at $X_{F,O}$=0.7 in nitrogen-diluted methane jet flames. The results show that the naissance is initially from the buoyancy-induced self-excitation with 12.524 Hz at U_O=1400 cm/s; at U_O=1500 cm/s, the buoyancy-induced self-excitation gives birth to another buoyancy-induced self-excitation with the frequency of 8.906 Hz while its own frequency slightly increases. It should be noted that, at U_O=1700 cm/s, the buoyancy-induced self-excitation has the frequency of 13.36 Hz; this spawns its sub-harmonic (6.67 Hz) frequency and then the sub-harmonic frequency can be inferred to the buoyancy-induced self-excitation observed in the group of Chung [1, 2]. Since that, the sub-harmonic frequency plays a role of the fundamental mode of the buoyancy-induced self-excitation with the order of 1 Hz. For the first time in his cyclic duration, the first harmonic frequency was not twice; hereafter the harmonic frequencies are of overtones for another birth. At U_O=1800 cm/s, the buoyancy-induced self-excitation due to a flame flicker has the frequency of 14.355 Hz; the fundamental frequency of the derived buoyancy-induced self-excitation is 5.28 Hz and its harmonic frequency is 10.44 Hz. At U_O=1900 cm/s, the buoyancy-induced self-excitation due to the flame flicker is 14.201 Hz; the fundamental frequency of the derived buoyancy-induced self-excitation is 3.94 Hz; the first and second harmonic frequencies are 7.902 and 11.90 Hz, respectively. Further increase of nozzle exit

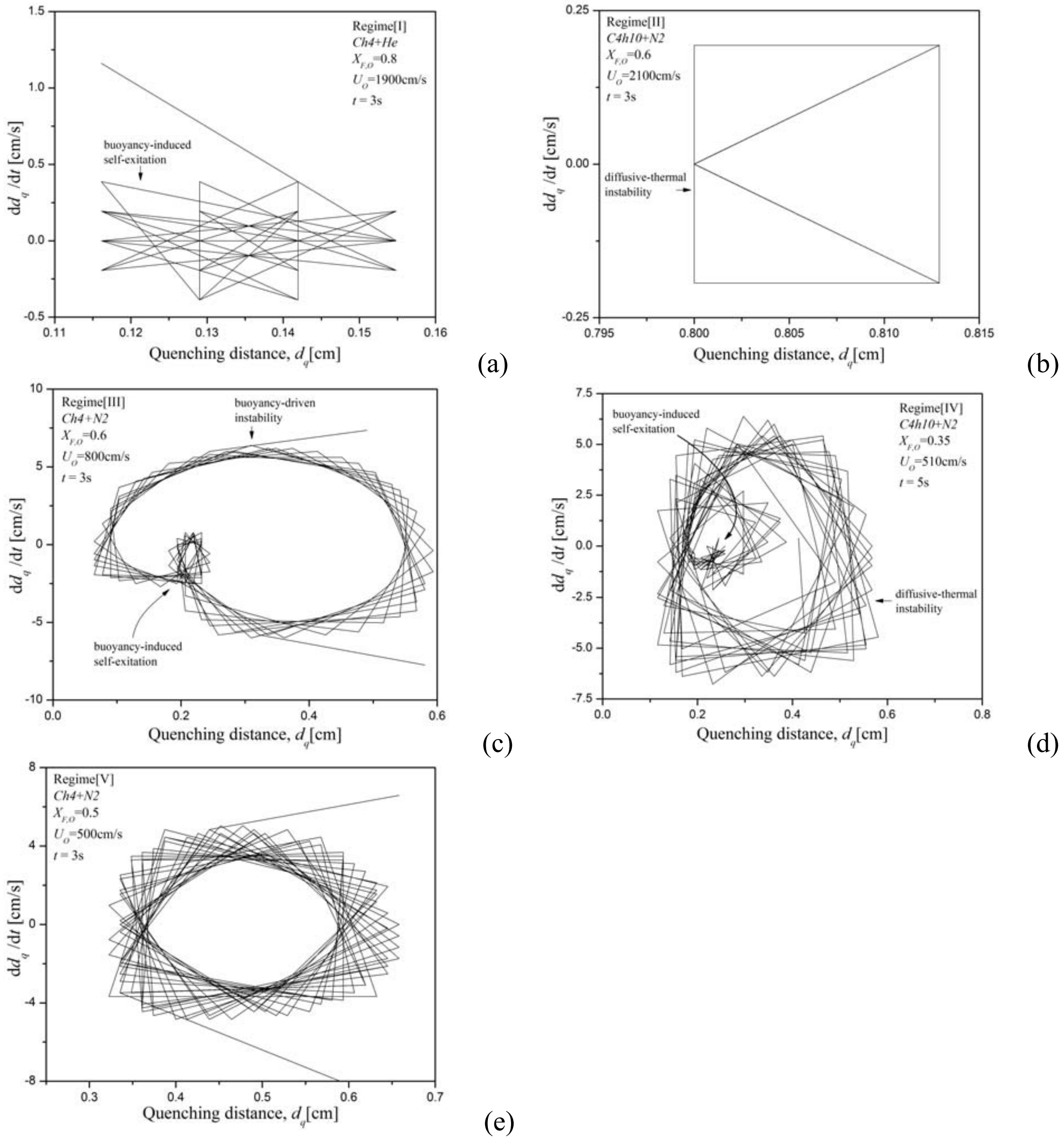

Figure 7 Phase diagrams of h and *dh/dt* for various oscillation modes.

velocity increases the number of overtones, i.e., at U_O =2300 cm/s, the number of overtones are 9. Note that the fundamental frequency of the derived buoyancy-induced self-excitation decreases with nozzle exit velocity, having the same tendency of the previous study [1, 2]. Consequently this convinces that the buoyancy-induced self-excitation with the frequency of the order of 1 Hz observed in the previous study is derived from the buoyancy-induced self-excitation with the order of 10 Hz due to a flame flicker. Fig. 6b also shows that, at U_0 = 2350-2400 cm/s, the buoyancy-induced self-excitation due to a flame flicker as well as the derived buoyancy-induced self-excitations abrupt disappear, thus being inferred that the derived buoyancy-induced self-excitations lost their driving source due to the disappearance of the buoyancy-induced self-excitation due to a flame flicker forces. In such situation, the attached flame becomes stationary. However, at U_0 = 2450 cm/s, the buoyancy-induced self-excitation forms again, this gives rise to the fundamental derived buoyancy-induced self-excitation and their overtones when the nozzle exit velocity increases, and so on.

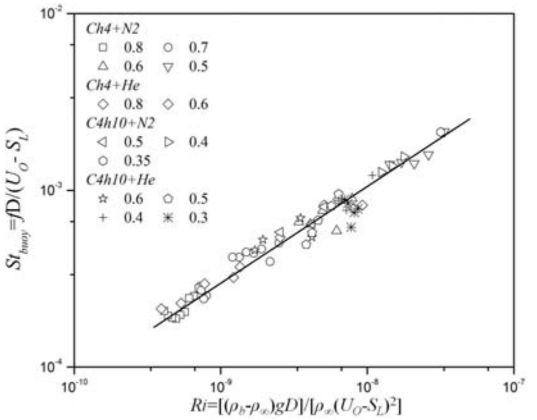

Figure 8 The dependency of Strouhal number due to buoyancy-induced self-excitation on Richardson number.

Based on the concrete genealogy in such buoyancy-induced self-excitations, further exploration may be required to find what the self-excitation modes are. The phase diagrams of the individual self-excitations in terms of dd_q/dt and d_q in the regimes I, II, III, IV and V are demonstrated in Fig. 7. The quenching distance was defined as the gap between the edge flame and nozzle exit. This means that the jet flame is not lifted in that heat-loss-induced self-excitation does not occur and the lowest quenching distance is attached to nozzle exit. In Fig. 7the vertical axis implies the edge flame displacement velocity obtained from temporal variation of edge flame displacement for 3 s. Fig. 7a corresponds to the case with only the buoyancy-induced self-excitation due to a flame flicker in the regime I. In such a mode, the displacement amplitude and velocity are relatively small; and the displacement speed has a variety of values; the motion center in the self-excitation occurs particularly at the quenching distance of 0.135 cm. Fig. 7b corresponds to the case with only the Lewis-number-induced self-excitation in the regime II. The result shows that the edge flame has the symmetrical, constant (positive and negative) values; the displacement is much larger than that in Fig. 7a. Fig. 7c is the coupled form of the buoyancy-induced self-excitation and the derived buoyancy-induced self-excitation only with the fundamental frequency in the regime III. The displacement and displacement speed are much larger than those with only the buoyancy-induced self-excitation in Fig. 7a and with only the Lewis-number-induced self-excitation in Fig. 7b. It is also indicated that the maximum edge flame displacement speed occurs at the center of the quenching distance. Furthermore, similarly to that in Fig. 7a, the buoyancy-induced self-excitation due to the flame flicker causes the small displacement and the motion center in the self-excitation also occurs at a specific location around d_q=0.2 cm. Fig. 7d, classified into regime IV, corresponds to the coupled form of the buoyancy-induced self-excitation due to the flame flicker (regime I) and Lewis-number-induced self-excitation (regime II). Therefore, the phase diagram shows such the mixed form of Fig. 7a and Fig. 7b that various displacement speeds, in the large, distinct displacement with the constant speed displacement, appears according to quenching distance. Fig. 7e is classified into the regime V and corresponds to the case that all the self-excitation modes are mixed. The result shows that the mode shape is mainly determined by the buoyancy-induced self-excitation due to the flame flicker as well as the derived buoyancy-induced self-excitations while the Lewis-number-induced self-excitation is minor. The comparison between Figs. 7d and 7e represents that the buoyancy-induced self-excitation due to a flame flicker does not suppress Lewis-number-induced self-excitation; meanwhile, once the buoyancy-induced-self-excitation gives birth to the derived buoyancy-induced self-excitations, the derived buoyancy-induced self-excitation significantly restrains Lewis-number-induced self-excitation. This can be the reason why it was hard for the Lewis-number-induced self-excitations [3, 5-8] to be observed in jet flame configurations; thereby the buoyancy-induced self-excitation [1, 2, 4] has been overwhelmingly found in laminar lifted flames.

Figure 8 depicts the characterization of buoyancy-induced self-excitation due to a flame flicker with the functional dependency of the Strouhal number on the Richardson number at various flame conditions. In the current experiments, the buoyancy-induced self-excitation frequencies due to a flame flicker were in range of 9.33 – 14.55 Hz. The results show that the Strouhal number correlates well with the Richardson number. This functional dependency was very similar to that observed in non-reacting thermal plumes [13]. The best fit is $St_{buoy.} = 25.08Ri^{0.54}$ with a correlation coefficient of 0.991. However, the characterizations for Lewis-number-induced self-excitation and the derived buoyancy-induced self-excitation remain to be solved.

Concluding Remarks

Self-excitations in horizontally and vertically injected laminar free-jet flames with applied DC electric fields are experimentally investigated and distinctly classified into three: a buoyancy-induced self-excitation due to a flame flicker, a Lewis-number-induced self-excitation, and the fundamental mode as well as their overtones of a derived buoyancy-induced self-excitation. The application of DC electric fields to jet flames was experimentally designed to suppress heat-loss-induced self-excitations to highlight the definite difference between Lewis-number-induced self-excitation and the derived buoyancy-induced self-excitation with the same order of 1 Hz.

In horizontally injected jet methane and butane flames diluted with nitrogen and helium, buoyancy-induced self-excitations are not observed due to the suppression of buoyancy, thereby suggesting that horizontal injection should present a good way to suppress buoyancy effects. In such horizontal injection of butane jet diluted with helium and nitrogen and thereby Lewis numbers much larger than unity, Lewis-number-induced self-excitations in the range of 2.433~5.552 Hz are clearly observed. The mechanism of Lewis-number-induced self-excitation can be reasonably explained. The applied DC electric field significantly increases the edge flame speed, this makes the edge flame be more attached to the nozzle exit, the jet flame can be stretched and lengthy, and the radii of curvature of edge flame and near the tip of rich premixed wings can be reduced. Then, the thermal diffusion is concentrated near the tip of rich premixed wings, leading to the migration of premixed wing to an upstream location due to the enhanced propagation speed. The migrated edge flame to the upstream location encounters the correspondingly assigned, increased fuel concentration gradient at the triple point and furthermore the diffusive supply of reactant masses can be restricted due to the Lewis numbers much larger than unity. Then the edge flame tends to migrate downstream. During the half stroke of the self-excitation, these natures forces the tip part of rich premixed wings to advance upstream and the edge flame to recede downstream. Again, the receded edge flame encounters the correspondingly assigned, reduced fuel concentration gradient at the triple point and furthermore the applied DC electric fields also increase the edge flame speed, thus advancing the edge flame upstream again. This nature can be the mechanism of Lewis-number-induced self-excitation.

The genealogy on buoyancy-induced self-excitations definitely shows that the buoyancy-induced self-excitation with $O(10)$ Hz due to a flame flicker causes the frequencies of the fundamental mode with $O(1)$ Hz as well as their overtones of a derived buoyancy-induced self-excitation. The phase diagrams on the distinct regimes on the basis of self-excitation modes describe the different behaviors of their own self-excitation well. The buoyancy-induced self-excitation due to a flame flicker has the small displacement and also various displacement speeds at the same quenching distance. The Lewis-number-induced self-excitation shows the constant positive and negative displacement speeds. Meanwhile the derived buoyancy-induced self-excitation with the similar frequency to the Lewis-number-induced self-excitation indicates much larger displacement amplitude and displacement speed in comparison to those in buoyancy-induced self-excitation due to a flame flicker and Lewis-number-induced self-excitation. In such situation, once the buoyancy-induced self-excitation with $O(1)$ Hz is derived from the buoyancy-induced self-excitation caused by a flame flicker, the mode significantly suppresses Lewis-number-induced self-excitation. This can be the reason why it was hard for the Lewis-number-induced self-excitations [3, 5-8] to be observed in jet flame configurations; thereby the buoyancy-induced self-excitation [1, 2, 4] has been overwhelmingly found in laminar lifted flames.

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