Buoyancy Effect on Stable and Oscillating Lifted Flames in Coflow Jets for Highly Diluted Propane

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Introduction

Lifted flames in laminar jets have been studied extensively to identify flame stabilization mechanism. The base of a laminar lifted flame exhibits a tribrachial structure, consisting of a lean and a rich premixed flame wings and a trailing diffusion flame, all extending from a single location[1].

Recently, attentions are focused on the lifted flame behavior in coflow jets. One of the merits in adopting coflow is its numerical advantage over free jet, especially when large size nozzle and low jet velocity are adopted[2, 3]. Won *et al.*[3] investigated lifted flame behavior experimentally in coflow of highly diluted propane and air. It has been observed that when a large size nozzle with low jet velocity is used, flow charactersitics are different between cold and reacting flow due to the buoyancy effect by the differences in density among propane, air and burnt gas. In a certain range of fuel jet velocities and fuel dilution, vertically oscillating lifted flames were observed. In the present study, flame characteristics in such buoyant jets are investigated numerically to elucidate the effect of buoyancy on lifted flames.

Numerical Scheme

To simulate detailed flow field of lifted flames, the numerical solver is based on a direct numerical simulation(DNS) code. Because of low speed jet condtion, low Mach number approximation is adopted to simplify governing equations[4], in such a way that the zeroth order pressure term is constant over computational domain for an open system and the first order term is governed by the Poisson equation. To save calculation time, nonuniform grid system is applied by embedding fine grids in the vicinity of flame region. Consequently, Poission equation solver should be iterative that multi-grid method with fast iterative algorithm is adopted. A finite difference procedure on a staggered grid is adopted and time integration algorithm is that from Najm *et al*[5]. To emphasize hydrodynamic effect, chemical reaction is simplified to one-step global reaction. Thermodynamic and transport properties are calculated from CHEMKIN-II and TRANSPORT pacakage.

Results and Discussions

Cold and Reacting Flows

In a cold flow without considering the buoyancy, a flame can be initiated by imposing a high temperature ignition source near a partially premixed zone. Subsequent flame has spherical shape initially and then flame edge gradually forms a tribrachial structure. It has been confirmed that the tribrachial flame propagates along the stoichiometric line. Finally, it settles as a stationary flame. This kind of transient behavior can also be observed in case of buoyant flow.

A laminar jet of highly diluted propane-nitrogen mixture discharging vertically into surrounding coflow air has different characteristics from single component coflow or buoyancy-absent coflow jets. It has been observed experimentally[3] that the cold jet has circular cone shape since upwardly injected propane jet decelerates and forms a stagnation region. Then the fuel stream is carried by coflow air by forming a fan shape. The present numerical result predicts this behavior as shown in Fig.1a. In contrast to cold flow, the reacting flow with a lifted flame has no stagnation region by the buoyancy force induced from the burnt gas. Strong entrainment makes the flow field ahead of the flame edge contracted into the central region of the lifted flame (Fig.1b). To further illustrate buoyancy effect on lifted flames, the reacting flow with buoyancy is compared with non-buoyant reacting flow. Figure 2 shows that non-buoyant flame is stabilized at much lower height from the nozzle than the liftoff height of the buoyant flame. The non-buoyant diffusion flame is broader and longer than buoyant flame, which is narrower by the vertical acceleration of the hot gas by the buoyancy which entrains surrounding air as demonstrated by the streamlines.

Oscillating lifted flame

Under certain conditions, oscillating flames exist experimentally[3]. For the experimental condition of $X_{fuel} = 0.10$ and $U_{fuel} = 5.03$ cm/s, characteristics of numerically calculated oscillating flame is shown in Fig.3, where the height of flame base and tip vary during one cycle of oscillation with the frequency of 3.3 Hz, which agrees well with the experimental result. During one cycle of oscillation, the flame base kept on maintaining a tribrachial structure. The mechanism of oscillation can be explained by buoyancy effect[3]. During the falling period, lifted flame propagates upstream as a result of larger propagation speed compare to local flow velocity. As the flame migrates upstream, the fuel flux to the flame will increase as demonstrated by the streamlines in Fig.3. Consequently, flame length and buring rate increase, and buoyancy effect will be intensified. This leads to the increase in axial flow velocity. As the local flow velocity exceeds the propagation speed of tribrachial flame, the flame base will migrate downstream. This repetitive nature of buring rate and buoyancy could lead to flame oscillation. Figure 4 shows that buoyant flame has oscillating flame features, while non-buoyant flame does not exhibit such an oscillation. Therefore, this confirms that the buoyancy is the controlling mechanism for lifted flame oscillation.

References

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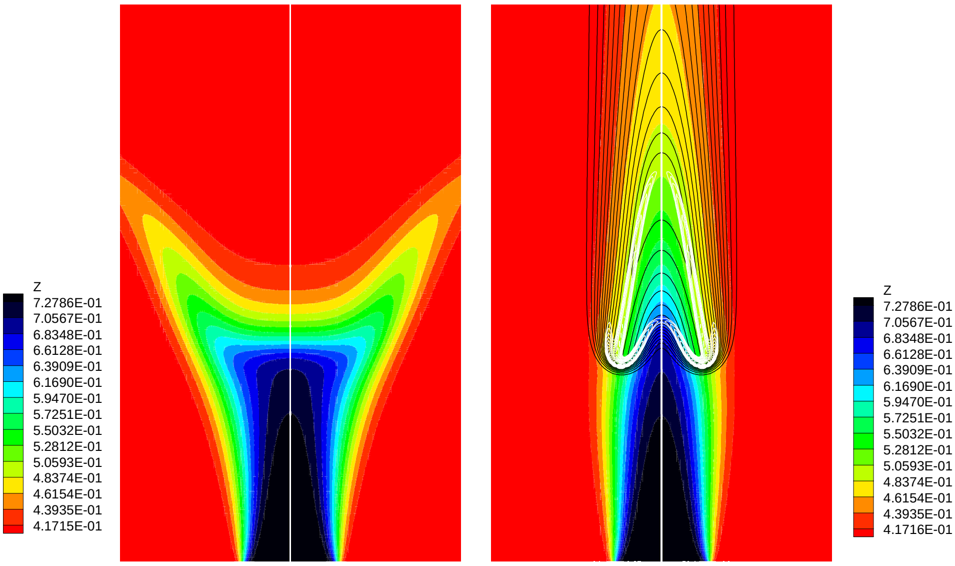

Figure 1. Numerical results of mixture fraction(contour) and temperature(lines) for $U_{fuel} = 7.07$ cm/s and $U_{coflow} = 9.40$ cm/s; (a) cold and (b) reacting flows.

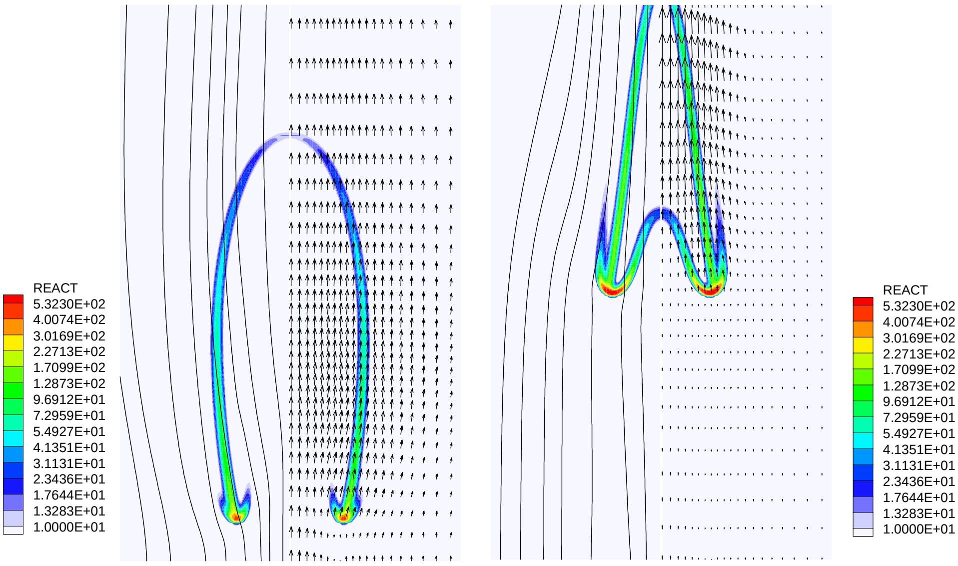

Figure 2. Reaction rate(contours), streamline(lines) and velocity vectors for $U_{fuel} = 10.49$ cm/s; (a) without buoyancy and (b) with buoyancy.

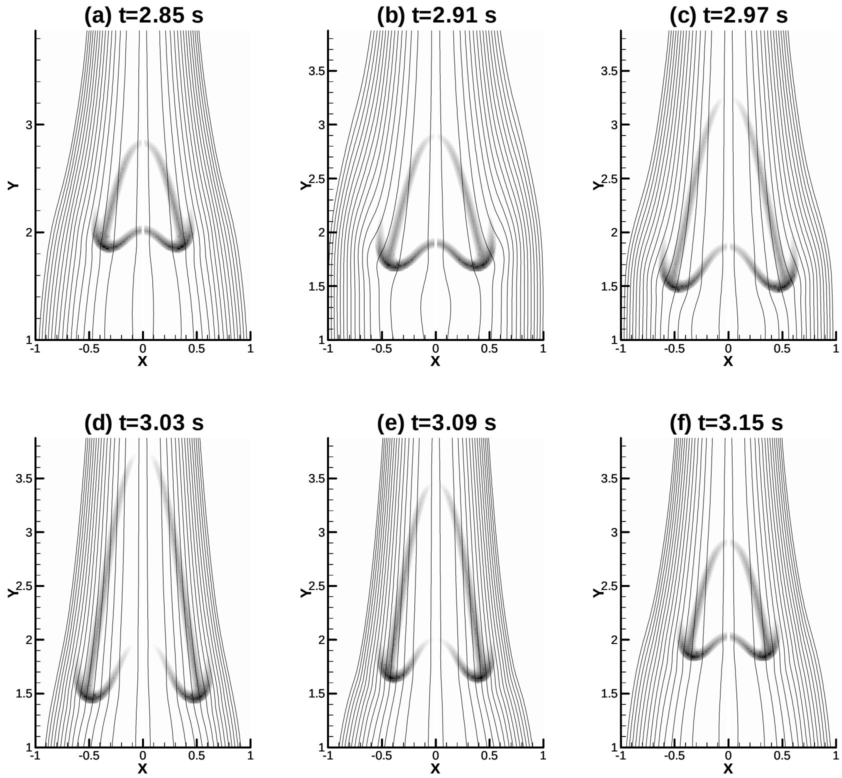

Figure 3. Numerical resluts for oscillating flame for $U_{fuel} = 5.03$ cm/s with buoyancy; streamline(contours) and reaction rate(lines).

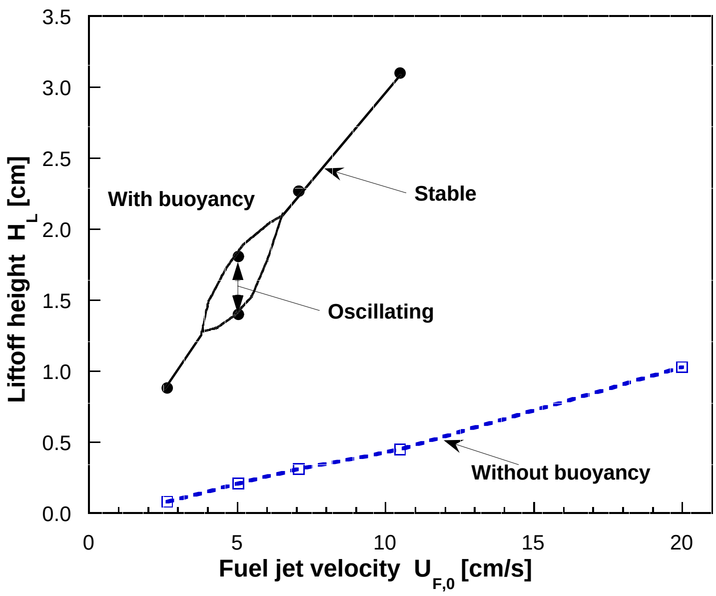

Figure 4. Liftoff height with jet velocities without buoyancy(dotted line) and with buoyancy(solid line).