Reattachment of Lifted Flames in Laminar Propane Jets

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Introduction

Characteristics of laminar lifted flames have been investigated to improve the understanding of turbulent lifted flames. In laminar jets with the Schmidt number greater than unity, a flame lifts off at a certain jet velocity and as jet velocity increases, liftoff height increases nonlinearly and then blowout occurs [1]. Since the leading edge of a laminar lifted flame has a tribrachial structure, the flame edge will be located along a stoichiometric contour and the propagation speed of tribrachial flame will balance with flow velocity. Using these characteristics, correlations of liftoff height with nozzle exit velocity, nozzle diameter and Schmidt number have been derived from the similarity solutions for velocity and fuel concentration. Such correlations have been substantiated from experiment [1,2].

The similarity solutions predicted that liftoff height can be varied from zero height to the height at which blowout occurs. However, experimental results demonstrated that a lifted flame abruptly reattached to the nozzle as flow rate decreases [1-3]. Consequently, the similarity prediction can not properly explain the reattachment mechanism and could pose a question about its validity of the stabilization mechanism of lifted flames. It implies that other theories in predicting lifted flames including the view of diffusion flame quenching [4,5] might be viable.

In the present study, based on the fact that the similarity solutions have a singularity near nozzle, the concept of virtual origin is implemented to the similarity solutions, through which the reattachment phenomena can be successfully predicted based on the balance of flow velocity and the propagation speed of a tribrachial flame.

Experiment

Experimental apparatus consists of a nozzle, a flow rate controller and a measurement system. The nozzle is made of a quartz tube having O.D. 3 mm and I.D. 1.5 mm. The tip of the tube is modified to form a convergent nozzle with the exit diameters of d = 0.153 mm, 0.177 mm and 0.215 mm with the contraction area ratios over 100 to obtain a nearly uniform velocity profile at the exit. Fuel used is C. P. grade (> 99%) propane which is diluted with air. Mass flow controllers (MKS) are used for flow rate control. A transparent square cylinder 800 x 800 x 950 mm (W x L x H) surrounds the nozzle to minimize the disturbances from the ambient. Liftoff height is measured by a cathetometer. Shadowgraphy is used to record the transient flame position variation during liftoff and reattachment. A highspeed camera (Kodak, Ekta Pro SR-ULTRA) captures images which are analyzed by a PC.

Results and Discussion

Liftoff Height and Reattachment

Figure 1 shows liftoff height with nozzle exit velocity u_0 for d = 0.177 mm and initial fuel mass fraction at nozzle exit $Y_{F,0}$ = 1.0. As flow rate increases, the flame lifts off and stabilized at a certain axial distance x_{LO} when $u_0 = u_{\mathrm{LO}}$. As u_0 further increases, liftoff height H_L increases nonlinearly with u_0, and then blowout occurs at u_{BO}. With decreasing u_0, H_L decreases upto a certain axial distance x_{RA} when $u_0 = u_{\mathrm{RA}}$. Then, the flame instantaneously reattached to the nozzle. The liftoff height can be correlated as $H_L \propto u_0^n$ from the similarity solution [1,2].

It is a difficult task to predict the condition of liftoff because of complex flow pattern and heat transfer near nozzle. At the reattachment condition, it is expected that the similarity solutions could be applied since the liftoff height is still far away from the nozzle. Contrary to the experimental observation, the similarity solutions predict that liftoff height could continuously decrease to zero height.

It has been reported that the similarity solutions are applicable in the region far away from a nozzle exit and they are inaccurate close to a nozzle exit because of the singularity at the origin. Such an inaccuracy, therefore, can be a reason not to properly explain flame reattachment. To improve the accuracy of the similarity solution for velocity in the region close to a nozzle, a virtual origin has been frequently introduced and various methods have been applied to determine the location of the virtual origin [6,7].

The similarity solution for concentration has the same problem, however, studies on the virtual origin for concentration rarely exist [8]. Considering that the velocity profile with a virtual origin agrees well with experiment, it is desirable to introduce a virtual origin to concentration.

Analysis with Virtual Origin

Since the leading edge of a lifted flame is located along a stoichiometric contour [9], the dimensionless axial velocity along the stoichiometic contour U_{st} can be derived as follows when considering the virtual origins for velocity X_v and concentration $X_{v,F}$

$$U_{st} = \frac{3}{32}\frac{1}{X+X_v}\left[1+\left(\frac{X+X_{v,F}}{X+X_v}\right)^2\left\{\left(\frac{2\mathrm{Sc}+1}{32}\frac{1}{X+X_{v,F}}\frac{Y_{F,0}}{Y_F^*}\right)^{\frac{1}{2\mathrm{Sc}}}-1\right\}\right]^{-2} \quad (1)$$

where X is the nondimensional axial distance.

This profile is plotted in Fig. 2 for propane fuel ($\mathrm{Sc_F}$>1) together with the similarity solutions. Previous study [8] suggested that the unsteady propagation speed of a tribrachial flame S_{tri} decreases with radial fuel concentration gradient at the flame base. Thus, it is assumed that the local flame propagation speed is linear with axial distance in Fig. 2 and is depicted as straight lines.

A flame can be stabilized, say at point B when $u_0 = u_{\mathrm{LO}}$. At increased jet velocity, blowout occurs when $u_0 = u_{\mathrm{BO}}$ at point A. As jet velocity decreases, a stationary lifted flame could move upto the point C, which corresponds to the maximum axial velocity along the stoichiometric contour. If the flow velocity decreases further, e.g., to the point D, the flame will be reattached to the nozzle, since S_{tri} is larger than local velocity. Although relative magnitude between u_{RA} and u_{LO} can not be estimated, it is predicted $u_{\mathrm{RA}} < u_{\mathrm{LO}} < u_{\mathrm{BO}}$ since the flame reattaches to the nozzle for $u_0 < u_{\mathrm{RA}}$ and this range is unstable since the flow velocity increases with axial distance. In such a case, a stationary lifted flame can not be stabilized [9]. As a result, a hysterisis between reattachment and liftoff could occur, as demonstrated in Fig. 1.

For propane jets, the liftoff height can not be calculated from the solutions with the virtual origins since the data for the propagation speed of tribrachial flame have not been reported. However, the qualitative behavior of liftoff height with initial fuel mass fraction can be calculated as shown in Fig. 3 based on the previous study demonstrating that S_{tri} is relatively constant for stationary lifted flames [9]. Even assuming the propagation speed varies with fuel concentration gradient, similar results can be obtained and the quantitative difference is minimal. There exists a turning point, thus the liftoff height near a reattachment will be deviated from the correlation of $H_L \sim u_0^n$ as demonstrated in Fig. 1.

Flame Displacement Speed during Reattachment and Liftoff

One method to substantiate the axial velocity profile along a stoichiometric contour (Fig. 2) is to measure the transient behavior of flame displacement speed during reattachment and liftoff. At the moment of liftoff or reattachment, the displacement speed S_d has to satisfy $S_d / u_0 = \left| U - S_{tri} / u_0 \right|$.

Assuming S_{tri} is constant, S_d at reattachment and liftoff is depicted by dotted lines in Fig. 4. Horizontal axis is the nondimensional axial distance normalized by the liftoff height at reattachment $X^* = X_{\mathrm{RA}}$=0.17 or liftoff $X^* = X_{\mathrm{LO}}$=1.84.

Ko *et al.* [10] proposed that the flame propagation speed varied with the gradient of fuel mass fraction along a stoichiometric contour. Because the flame speed data with fuel mass fraction has not been reported for propane, the proposed correlation for methane is used for propane to evaluate qualitative behavior. The results are represented by solid lines in Fig. 4..

Regardless of the modellings of flame propagation speed, the characteristics of displacement speed during reattachment and liftoff are qualitatively the same. However, the behavior between reattachment and liftoff are quite different. The displacement speed at liftoff rapidly increases and decreases slowly whereas the displacement speed at reattachment monotonically decreases.

To confirm the prediction, the flame location is measured with the highspeed camera at 2000 fps. The predictions, as shown in Fig. 4, agree qualitatively well with the experimental data in Fig. 5. This agreement shows that the propagation characteristics of a tribrachial flame are maintained during liftoff and reattachment and the solutions with the virtual origins are useful in analyzing the characteristics of flames in jets.

References

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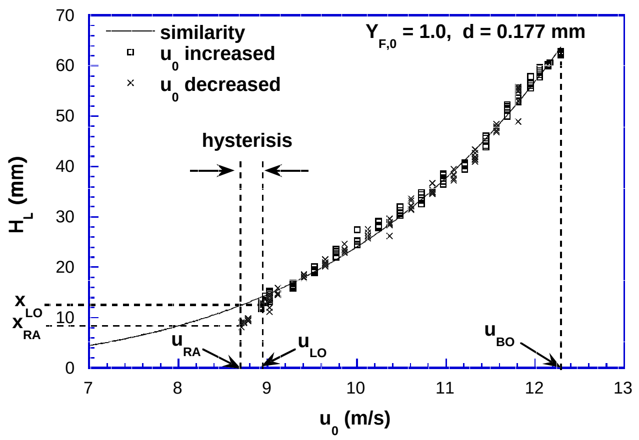

Figure 1 Comparision of liftoff height between experiment and similarity prediction with nozzle exit velocity.

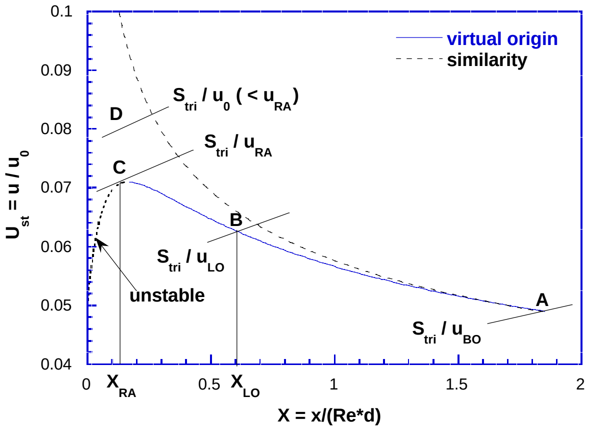

Figure 2 Calculated axial velocity profile along stoichiometric contour for propane jet.

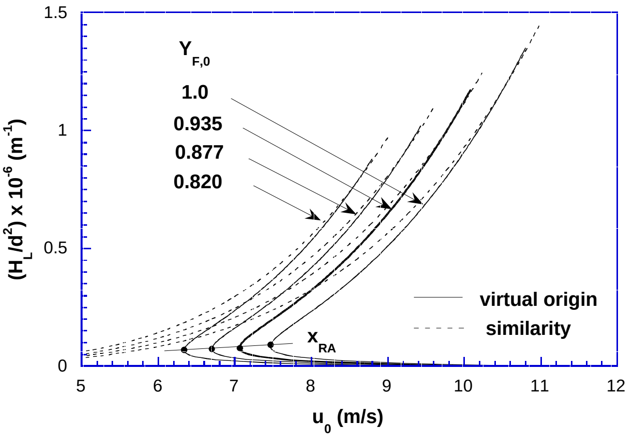

Figure 3 Calculated liftoff height with nozzle exit velocity.

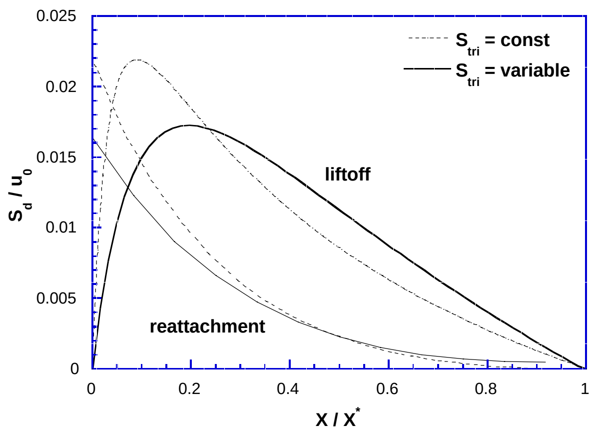

Figure 4 Calculated transient displacement speeds during liftoff and reattachment.

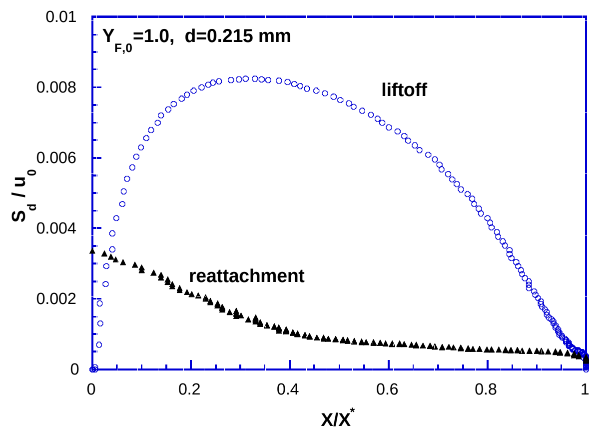

Figure 5 Transient displacement speeds during liftoff and reattachment.