# Self-oscillating Laminar Lift-off Flames

**Sung Hwan Yoon[1], Jeong Park[1*], Oh Boong Kwon[1], Jin Han Yun[2], and Sang In Keel[2]**

[1] School of Mechanical Engineering, Pukyong National University,
San 100, Yongdang-dong, Nam-gu, Busan 608-739, Korea
[2] Eco-Machinery Research Division, Korea Institute of
Machinery & Materials, 171 Jang-dong, Yuseong-gu, Daejeon 305-343, Korea

## 1. Introduction

It has been shown that the lateral conduction heat losses cause edge flame oscillation of low frequency at low strain rate flames [1], and also recognized that volumetric heat losses not only enhance edge flame oscillations but can also trigger oscillations under conditions where in their absence the flame is stable [2]. The flame may migrate downstream because of the reduced flame propagation velocity caused by the heat loss in laminar lift-off flame. This implies that the scalar dissipation rate decreases at the downstream location and the flame response of the edge flame is that of the middle branch on a S-curve. Then the edge flame, which has an intrinsically dynamic behavior, intends to jump up the upper branch in the S-curve unless the flame is blown out. This is so because the middle branch solution is unstable. If the increased propagation velocity at the downstream location is positive, the edge flame is forced to restore to an upstream location again. This cyclic stroke may cause edge oscillation in laminar lift-off flame (so called self-oscillation). In the present study experiments are performed to clarify edge flame oscillations in laminar free-jet lift-off propane flames diluted with nitrogen: self-oscillation, buoyancy-induced oscillation, and the oscillation due to diffusive-thermal instability. Fuel nozzles of the diameter of 0.1mm and 1.0mm are also used to elucidate effects of flame curvature in edge flame oscillation and flame stability.

## 2. Experimental Setup and Methods

The lift-off flame test facility, consists of a free jet rig, oriented vertically up, a flow control system, a digital camera system, and an acrylic compartment for the suppression of external disturbance. Fuel nozzle tubes have diameters of 0.1 and 1.0 *mm* and lengths of 120 and 360 *mm* in order to be fully developed. The free-jet rig is mounted inside an acrylic compartment (50 *cm* x 50 *cm* x 150 *cm*), in which a series of fine mesh screens are installed in the low and upper parts in order to minimize outside disturbances.

## 3. Results and Discussion

Figure 1 shows flame stability map as a function of fuel jet exit velocity and fuel mole fraction for the fuel tube diameter of 0.1 *mm*. It should be noted that there is not a regime of stabilized lift-off flame for the fuel tube diameter of 0.1 *mm*. Once an attached flame are lifted off, the lifted flame oscillate for $X_{F,O}$>0.4. Meanwhile all the flames oscillate irregularly with about 0.02 Hz in the regime of oscillating lift-off flame. The low frequency oscillation is quite different from those in the previous study [3] that was responsible for fuel Lewis number and indicated an oscillation of 2 Hz as the flame length changed. The fuel Lewis numbers at $X_{F,O}$=1.0 and 0.4 are 0.53 and 0.98, respectively, and those at $X_{F,O}$<0.4 are larger than unity. Therefore such flame oscillations in Fig. 1 are not attributed to the diffusive-thermal instability caused by fuel Lewis number larger than unity. Fig. 2 illustrates temporal

**Correspondence to: jeongpark@pknu.ac.kr** 

variations of typical lift-off height for (a) a pure self-oscillation at $X_{F,O}$=0.55, *V*=22.0 *m/s*, D=0.1 *mm* and (b) the combined form of a buoyancy-induced oscillation and a self-oscillation at $X_{F,O}$=0.55, *V*=24.1 *m/s*, D=0.1 *mm*. Meanwhile the temporal signal of lift-off height indicates a combined flame

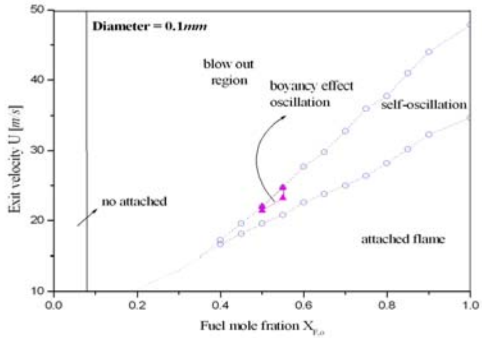


Fig. 1 Flame stability map as a function of fuel jet exit velocity and fuel mole fraction in laminar free-jet lift-off propane flame diluted with nitrogen; *D*=0.1 *mm*.

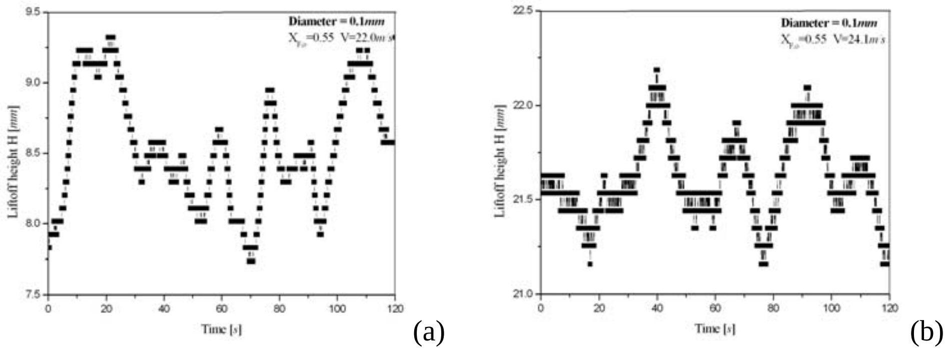


Fig. 2 Variations of typical lift-off height for (a) a pure self-oscillation at $X_{F,O}$ =0.55, *V*=22.0 *m/s*, *D*=0.1 *mm* and (b) a combined form of buoyancy-induced oscillation and self-oscillation at $X_{F,O}$ =0.55, *V*=24.1 *m/s*, *D*=0.1 *mm*.

oscillation aspect which has a little bit higher frequency together with a very low frequency in Fig. 2b. It may be required to analyze the frequency response characteristics of lift-off height in order to elucidate the difference between the two oscillations.

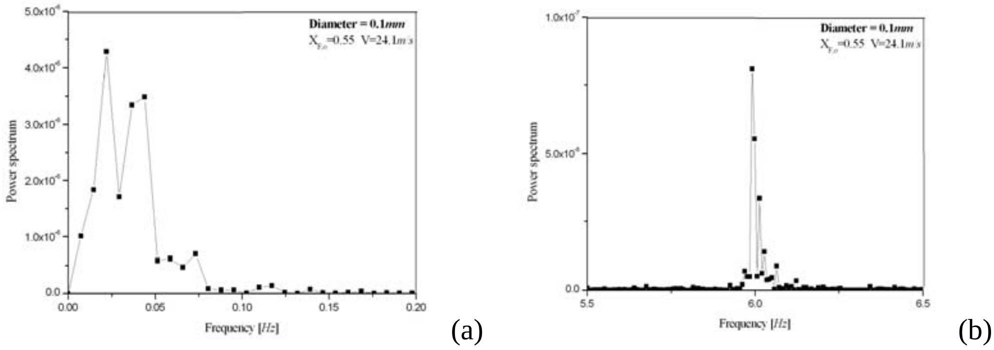


Fig. 3 Power spectrum of lift-off height for a combined form of a self-oscillation and buoyancy-induced oscillation in the ranges (a)less than 0.2Hz and (b)between 5.5 and 6.5Hz at $X_{F,O}$=0.55, *V*=24.1 *m/s*, D=0.1 *mm*.

Fig. 3 depicts power spectrums of lift-off height for a pure self-oscillation in the ranges (a) less than 0.2 Hz and (b) between 5.5 and 6.5 Hz for the combined form of buoyancy-induced oscillation and self-oscillation at $X_{F,O}$=0.55, *V*=24.1 *m/s*, D=0.1 *mm*. Fig. 3 also shows that there exists an oscillation with the relatively high frequency of 6.0 Hz in addition to the flame oscillation with the low frequency of 0.02Hz. The flame oscillation of lift-off height (2.5-5.0Hz in their study) has already been observed in laminar co-flow lift-off flames and verified to be relevant to buoyancy through experiments and numerical simulations with various gravity conditions [4]. Furthermore the flame displacement due to the flame oscillation with higher frequency, caused by buoyancy, is relatively quite small compared to that with the low frequency as shown in Fig. 2. As a result the large flame displacement due to the flame oscillation with the frequency of 0.02Hz in Fig. 1 is not responsible for buoyancy. Meanwhile increase in the radius of curvature in triple flame may extend the regime of oscillating lift-off flame since the flame propagation velocity increases. We conducted the same experiments with the burner diameter of 1.0 *mm* because the order of the radius of curvature in triple flame is relevant to fuel tube diameter.

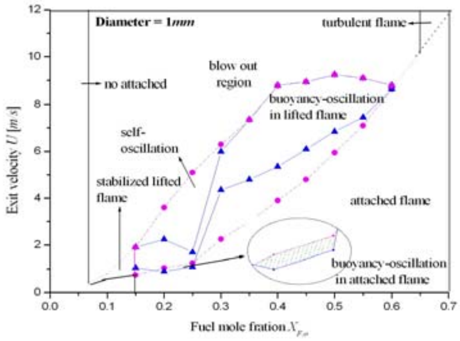


Fig. 4 Flame stability map as a function of fuel jet exit velocity and fuel mole fraction in laminar free-jet lift-off propane flame diluted with nitrogen; *D*=1.0 *mm*.

Fig. 4 describes flame stability map as a function of fuel jet exit velocity and fuel mole fraction with the fuel tube diameter of 1.0 *mm*. There exists a narrow regime of stabilized lift-off flame without flame oscillation, which corresponds to the region between the solid and dot lines at $0.07<X_{F,O}<0.15$, differently from that with the burner diameter of 0.1 *mm*. The dot-shaded regime at $0.20< X_{F,O} <0.25$ means that attached flames oscillate due to buoyancy similar to those found in laminar coflow lift-off flame [4]. The flame conditions between the circle symbols at $0.15< X_{F,O} <0.60$ represent the regime of self-oscillation. It is seen that the regime of oscillating lift-off flame shifts to a much lower fuel mole fraction $X_{F,O}$ =0.15 from the comparison between Figs. 1 and 4. This is because the flame propagation velocity increases due to the increase of the radius of flame curvature in the triple flame. Furthermore Fig. 4 also indicated that for the burner diameter of 1.0 *mm* the regime of oscillating lift-off flame can be extended to $X_{F,O}$ <0.4 at which fuel Lewis numbers are larger than unity. Then it may be also required to evaluate the contribution of fuel Lewis number in the regime of oscillating lift-off flame.

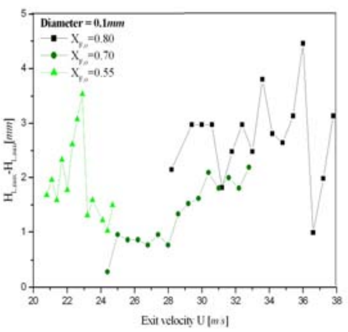


Fig. 5 Variations of the difference between maximum and minimum lift-off heights due to flame oscillation with fuel tube exit velocity for various fuel mole fractions; *D*=0.1 *mm*.

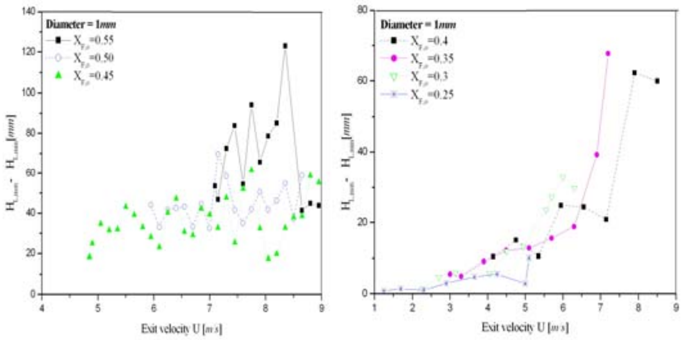


Fig. 6 Variations of the difference between maximum and minimum lift-off heights due to flame oscillation with fuel tube exit velocity for fuel mole fractions in cases of (a) $Le_F$ <1 and (b) $Le_F$ >1; *D*=1.0 *mm*.

Fig. 5 shows variations of the difference between maximum and minimum flame displacements with fuel tube exit velocity for various fuel mole fractions in the regime of oscillating lift-off flame with the burner diameter of 0.1 *mm*.

Fig. 6 is the same plots at (a) fuel mole fractions for fuel Lewis numbers less than unity and (b) those larger than unity with the burner diameter of 1.0 *mm*. As shown in Figs. 5 and 6a the difference between maximum and minimum flame displacements vary irregularly for fuel Lewis numbers less than unity in the regime of oscillating lift-off flame. It should be also kept in mind that there were not oscillating lift-off flame conditions at fuel Lewis numbers larger than unity. This implies that the main cause of irregular flame oscillation is attributed to only a pure self-oscillation for fuel Lewis numbers less than unity. However for fuel Lewis numbers larger than unity in Fig. 6b the difference between maximum and minimum flame displacements increases in increase of fuel tube exit velocity. This is because the flame displacements due to self-oscillation are overlapped by the flame oscillation caused by diffusive-thermal instability. Furthermore the increased flame stretch due to the increase in fuel tube exit velocity also augments the imbalance of mass- and thermal-diffusions.

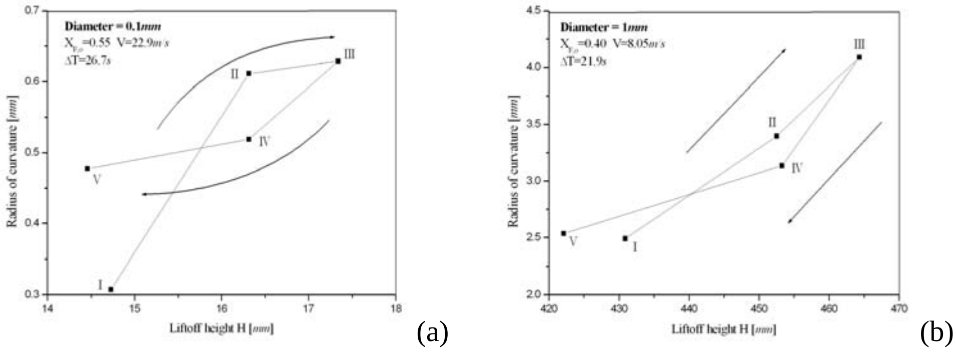


Fig. 7 Variations of radius of curvature at triple point with lift-off height at (a) $X_{F,O}$=0.55, *V*=22.9 *m/s*, D=0.1 *mm* and (b) $X_{F,O}$ =0.40, *V*=8.5 *m/s*, D=1.0 *mm*.

Figure 7 shows variations of the radius of curvature at triple point with lift-off height at (a) $X_{F,O}$ =0.55, *V*=22.9*m/s*, D=0.1*mm* and (b) $X_{F,O}$ =0.40, *V*=8.5*m/s*, D=1.0*mm*. As shown in Fig. 7 the radius of curvature increases and decreases as the triple flame migrates downstream and upstream, respectively.

## Concluding Remarks

1. There is not the regime of stabilized lift-off flame for the fuel tube diameter of 0.1 *mm* whereas there exists that of stabilized lift-off flame for the fuel tube diameter of 1.0 *mm*.
2. The regime of self-oscillation is extended to lower fuel mole fraction, the regime of the combined form of buoyancy-induced oscillation and self-oscillation becomes broad, and that of the combined form of diffusive-thermal instability and self-oscillation appears at fuel Lewis numbers larger than unity for the fuel tube diameter of 1.0 *mm*.
3. In the combined form of buoyancy-induced oscillation and self-oscillation the amplitude of the flame displacement due to buoyancy is very small compared to that of self-oscillation.
4. It is seen that in the combined form of diffusive-thermal instability and self-oscillation the amplitude of the flame displacement increases in increase of fuel tube exit velocity at fuel Lewis numbers larger than unity.

## References

[1] J.S. Park, D. J. Hwang, J. Park, J.S. Kim, S. Kim, S.I. Keel, T.K. Kim, S.S. Noh, Comust. Flame 146 (2006) 612-619.
[2] V.N. Kurdymov, M. Matalon, Combust. Flame 139 (2004) 329-339.
[3] M. Furi, O. Papas, P. A. Monkewitz, Proc. Combust. Inst. 28 (2000) 831-838.
[4] B.J. Lee, S.H. Chung, *Combust. Flame* 107 (1997) 163-172.