Effect of gravity and beam diameter on flame oscillation phenomena induced by external laser irradiation

Masakazu TSUCHIMOTO, Osamu FUJITA, Teruaki HONKO, Yuji NAKAMURA, and Hiroyuki ITO

Hokkaido University, Kita13 Nishi8, Kita-ku, Sapporo, Hokkaido, Japan

1 Introduction

Instability during the flame propagation is one of the most interesting research topics because it could be a fundamental process of turbulent combustion, which appears in various types of industrial burner. To this date, a number of researches have been performed to gain the insight of its fundamentals[1-3]. It is well-known that there is various instability modes appeared in combustion processes ; for example, diffusive-thermal instability based on Lewis number of the mixture, hydrodynamic instability caused by thermal expansion, body-force instability (called Taylor instability) associated with the buoyancy-driven gas movement[4]. Nonetheless the novel past studies, little attempt has been made to make application to cause above instabilities by changing only one parameter. Therefore, it is our hope to have unique scheme to control the instability in order to understand its role on the combustion behavior.

Recently we have successfully developed the corresponding scheme to control instability by utilizing laser input into the propagating flame[5]. High-powered laser input causes the local temperature rise through the molecular energy absorption. By rough calculation, temperature is increased about 200 degrees by exposing 10W laser(beam diameter is 5mm) in 0.05 seconds at the area just behind the incident laser. As a result, the flame front shape is deformed along the laser path. Possible advantages of this scheme are : 1) no generation of flow disturbance, 2) thermal energy input is well-controlled by manipulating the laser character (e.g. power, beam diameter (Full-Width Half-Maximum), exposure time duration).

Fig.1 shows the example of still images during the flame propagation inside the transparent tube with incident laser exposure along the center axis. Considered combustible mixture is CO_2-diluted ethylene-oxygen mixture and ethylene is the absorption media here. Continuously applied laser exposure causes the local energy input along the center axis. As seen in the figure, "oscillatory-propagation-behavior" is clearly observed with laser input, and the oscillation is pronounced as the applied laser power is increased. Since this observation has been done in normal gravity environment, it is suspected that such observed oscillation mode is driven by buoyancy. And it is also suspected that flame front curvature has an effect on this oscillation phenomena. In this study, we have performed two series of experiments in order to

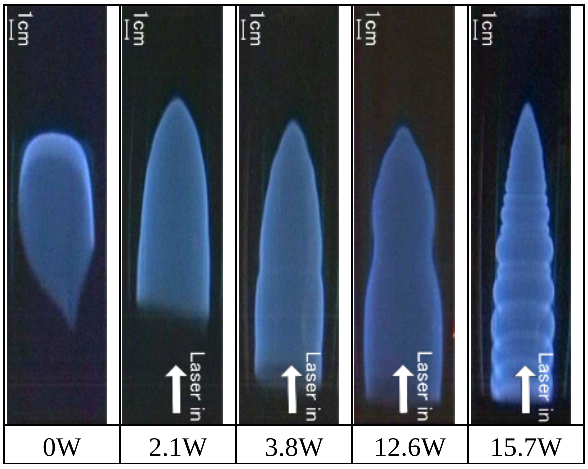


Fig.1 Still images of propagating ethylene-air premixed flames (tested gas is #3 ; see Table 1). with various applied laser powers in normal gravity condition. Propagating direction is from bottom to top. Laser is exposed from bottom (details are shown in Fig.2.)

investigate the key factor leading to this phenomena ; one is utilizing the microgravity environment to eliminate the buoyancy role on the flame propagation behavior, the other is using different laser beam diameter to change flame front curvature.

2 Experiment and imposed conditions

Fig.2 shows the schematic of the experimental apparatus. Propagation tube (transparent tube, inner diameter is 50mm and length is 450mm) filled with a test gas is placed vertically, and incident laser (CO_2 laser ; SYNRAD firestar v20, wavelength 10.6μm) goes into the tube from the bottom of it. Test premixed gas is the mixture of ethylene and oxygen and inert gas (consist of CO_2, He and N_2). Ethylene is the main absorption media in the present study according to the NIST chemical database[6]. Four solenoid valves are equipped at the one end of the tube to maintain the internal pressure as atmospheric level. Test premixed gas in the tube is exposed to the laser beam (Full-Width Half-Maximum is about 5mm, 6mm and 10mm) along the center axis continuously after the mechanical shutter is opened. In the present study, laser power is fixed at about 12W. Once the laser is irradiated, igniter (spark plug) is turned on to induce the ignition at the bottom of the tube. Flame propagates upward within 2 seconds and the propagation event is recorded by high-speed camera (nac HSV-500C[3]) with wide-angle lens. System sequence is controlled by the programmable controller.

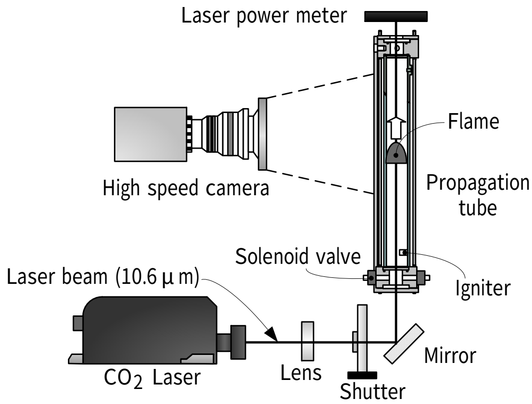


Fig.2 Schematics of experimental apparatus

Table 1 Tested gas composition

No.	C_2H_4	O_2	CO_2	other	ϕ	Le
#1	9%	20%	65.7%	He	1.35	0.68
#2	9%	17%	18.8%	N_2	1.59	0.94
#3	9%	21%	70%		1.28	0.84

*ϕ : equivalence ratio of the mixture, Le : Lewis number, number with percent denoted in the species is vol.%

Microgravity experiments were performed at MGLAB (microgravity laboratory at Japan, ~10^{-6}G for almost 5 seconds). After the microgravity started, ignition and subsequent flame propagation is made. Test premixed gas composition considered in this study is listed in Table 1. Note that the all selected gas compositions give almost the same burning velocity (25.2cm/sec) in 1-D configuration according to CHEMKIN software (Premix code). Since flame propagation speed could affect the instability behavior, above mixture selection (same burning velocity) could avoid the effect of flame speed itself on instability of flame front.

3 Effect of gravity on oscillation behavior

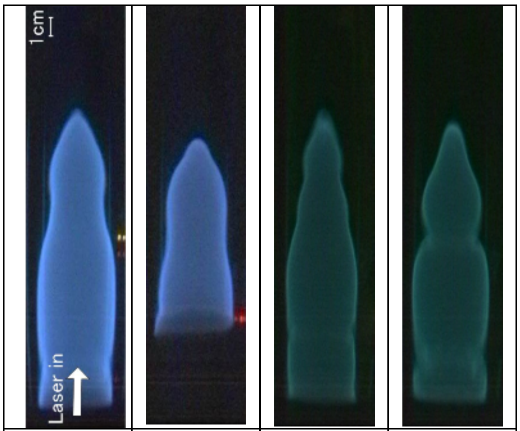
Fig.3 shows still images of the propagating flames with laser input in microgravity and in normal gravity. Two different kinds of gases (#1 and #2) were used for the comparison. Although flame propagation speed is different (e.g. #1 ;normal gravity 123cm/sec, microgravity 92cm/sec), as seen in the figure, oscillation is observed irrespective of the gravity level. This fact confirms that the presently-observed oscillation is not buoyancy-driven phenomena. Nonetheless slight differences in flame shape are notified depending on the gravity level ; deformation of the flame surface is a little larger in normal gravity condition, and flame front also become sharper in normal gravity condition. It implies that gravity force does not essentially control the onset of the oscillation (rather the incident laser flux does), but it does affect the oscillation mode during the flame propagation. Moreover, with careful comparison between #1 and #2, it can be seen that deformation of flame surface is more clearly achieved in #2. Since the flame propagation speed is equivalent to these gas mixtures, the difference notified here would be due to the Lewis number effect.

4 Effect of laser diameter on oscillation behavior

Fig.4 shows still images of the propagating flames with laser input of different beam diameters ; corresponding FWHM is 5mm, 6mm and 10mm, respectively. Two different gases (#2 and #3) were used in this series of experiment. As seen in the figure, as increase in the laser beam diameter, the deformation of flame shape becomes weak and period of oscillation becomes long, and finally oscillatory propagation hardly appears. According to the pictures, it can be seen that flame front has different curvature ; as increase in laser beam diameter, flame front curvature becomes mild. This indicates that flame curvature affects oscillatory propagation mode.

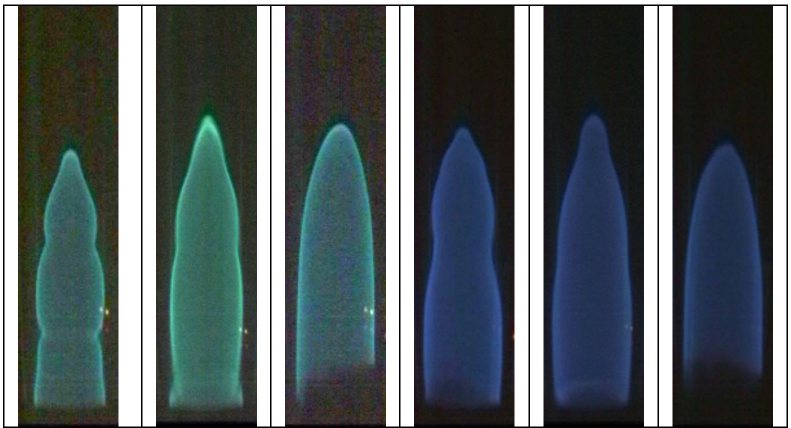
Some past study mentioned that flame curvature has an effect on flame propagation behavior. According to Yoshida's work[7], it has been revealed that local reaction at the flame front is strongly affected by its curvature by means of preferential diffusion. Moreover, Haq et al.[8] menthioned that turbulent intensity and standard deviation in flame curvature have strong relation and that flame front strcture is affected by individual flame curvature.

These papers imply that flame curvature affects flame front behavior and resulting propagation characteristics could be different dependence on the flame front curvature. To ensure this point, further study would be necessary.



1G	µG	1G	µG
#1		#2	

Fig.3 Still images of flame propagation with different gravity conditions (laser power 12W, FWHM 5mm)



FWHM 5mm	FWHM 6mm	FWHM 10mm	FWHM 5mm	FWHM 6mm	FWHM 10mm
#2			#3		

Fig.4 Still image of flame propagation with different Full-Width Half-Maximum (laser power 12W, normal gravity)

5 Possible flame oscillation generation mechanism

If Lewis number is the one of the key factors to generate the oscillation, following mechanism could be considered. Proposed mechanism is schematically illustrated in Fig.5. Since laser input induces the local preheating of the mixture, local flame speed is increased there. Consequently, we may have projected flame front along the laser pathway (see in (a)). Then, this projection is enhanced via Lewis number effect. Once strong projection is induced, it causes sudden cool down via stretch effect to cease further flame deformation (see in (b)). During the projected portion is paused, transverse flame propagation is proceeded to make the curvature of the flame front mild (see in (c)). Once flame front becomes round shape, again, flame front is projected to form (a). If above-mentioned procedure is periodically appeared, we may have observed flame oscillatory propagation.

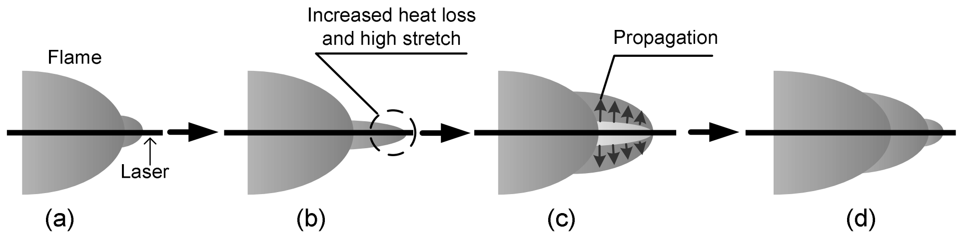


Fig.5 The hypothesis of flame oscillation mechanism

6 Concluding remarks

The effect of gravity and beam diameter on flame oscillation phenomena was investigated. Microgravity experiment assures the presently-observed oscillation is not induced by gravity, rather controlled by laser. Experiments with different laser beam diameter indicates that flame front curvature has an effect on oscillatory propagation behavior. Possible explanation to classify the oscillation character based on Lewis number of the mixture is proposed. Further study would be proceeded to clarify our speculations.

7 Acknowledgements

This was supported by "Ground-Based Research Program for Space Utilization" promoted by Japan Space Forum (1995-1996) and is supported by Grants-in-Aid for Scientific Research (KIBAN (B) #18360095) from MEXT Japan.

References

[1] Bechtold, J.K. et al. (2004), The role of radiative losses in self-extinguishing and self-wrinkling flames, Proceedings of the Combustion Institute, Vol.30, pp.177-184

[2] Kadowaki, S. (2005), The effects of heat loss on the burning velocity of cellular premixed flames generated by hydrodynamic and diffusive-thermal instabilities, Combustion and Flame, Vol.143, pp.174-182

[3] Breadley, D. et al. (2000), The development and structure of flame instabilities and cellularity at low Markstein numbers in explosions, Combustion and Flame, Vol.122, pp.195-209

[4] Williams, F.A. (1985), Combustion theory. 2nd Edition, The Benjamin/Cummings Publishing Copany, pp.349-365

[5] Fujita, O. and Ikeda, J. (2004), Flame oscillation phenomenon induced by external radiation, Proceedings of 42nd Symposium(Japanese) on combustion Japan, pp.185-186.

[6] The National Institute of Standards and Technology (NIST), http://webbook.nist.gov/chemistry/

[7] Yoshida, K. and Takagi, T. (1998), Transient local extinction and reignition behavior of diffusion flames affected by flame curvature and preferential diffusion, Proceedings of the Combustion Institute, Vol.27, pp.685-692

[8] Haq, M.Z. et al. (2002), Wrinkling and curvature of laminar and turbulent premixed flames, Combustion and Flame, Vol.131, pp.1-15