# Influences of Ultrasonic Waves on Blow-off Limits of Lifted Jet Flames

Mitsutomo HIROTA,\* Takuya TSUJI,\* Yuji NAKAMURA,\*\* and Tsutomu SAITO\* \* Muroran Institute of Technology, Dep. of Mechanical, Aerospace and Materials

Engineering

27-1, Mizumoto-cho, Muroran, 050-8585 JAPAN \*\* Hokkaido University, Division of Mechanical and Space Engineering N13W8, Kita-ku, Sapporo, 060-8628 JAPAN

### 1. Introduction

This research investigated the effects of an ultrasonic standing wave on a lifted jet flame to improve combustion stability near lean flammability limit conditions.

Recent research indicates that a high-response control mechanism must be used for a lifted flame. Generally, the stability of a lifted flame is related to the characteristics upstream of the flame edge. Specifically, the degree of premixing of the fuel and oxidizer changes the flame-edge propagation characteristics. When the flame edge can propagate, it stabilizes at the point where the propagation speed is equal to the unburned local flow velocity into the flame edge. Hirota et al.<sup>[1]</sup> reported that the burning velocity of an edge flame propagating through a mixture with a concentration gradient reaches its peak value at a gentle concentration gradient. Hirota et al.<sup>[2]</sup> also indicated that the flame edge exhibits hysteresis in response to instantaneous changes in the concentration gradient. These results demonstrate that an untouched high-response combustion control system taking into account the transitional response is necessary in order to improve lifted flame stability.

Lifted flames are usually controlled using vortices, which change the mixing state at the burner exit. These vortices are generated by loudspeakers,<sup>[3]</sup> piezoelectric actuators,<sup>[4]</sup> flap-like micro-actuators,<sup>[5]</sup> and so on. These systems can control the burning conditions, such as flame stability, because they influence the fluctuations of the mixing layer at the leading edge of the flame. The frequencies used are from 10 to 1000 Hz,<sup>[3]-[5]</sup> so that the influence of fluctuations uniformly spreads outwardly from the oscillating source. Specifically, the whole flow field changes on a large scale, including appropriate combustion regions, because of these low-frequency fluctuations.

Considering this background, the authors propose a combustion control system using high-frequency oscillation that affects local flow fields.<sup>[6]</sup> This oscillation has high directionality, since a plane wave and a standing wave are easily formed. There is considerable research indicating that high-frequency oscillation affects liquids.<sup>[7]</sup> In contrast, there are but few examples of combustion control using high-frequency oscillation on gases. Our research examines the effects of high-frequency oscillation upstream of the leading edge of a methane-air laminar lifted flame and the resulting flame structure. In particular, we report evidence of improved stability limits of the lifted

Hirota, M.

flame achieved increasing the blow-off limit. We also indicate the variation of preheat zone structures measured with the acetone-OH simultaneous Planar Laser Induced Fluorescence (PLIF) method.<sup>[8]-[10]</sup>

#### 2. Experiment Setup and Flame Behavior

Figure 1 schematically illustrates the oscillating system<sup>[6]</sup> and presents a photograph of the flame. This system consisted of a bolt-clamped Langevin transducer (BLT) with a horn, an oscillator power supply, a function generator, and a reflector. The center of the oscillating surface was aligned with that of the reflecting surface. The frequency ( $\lambda$ ) was 20.27 kHz, which was near the resonance frequency of this oscillating system. The amplitude was 105 V. The fixed distance between the oscillating and reflecting surfaces was 38mm. A standing wave of  $9\lambda/4$  could be generated with this distance. These oscillating and reflecting surfaces were established on a manual x-z axis linear stage, so that the position of this combustion control system could be changed. The center axes of the burner and oscillator cross at right angles. The height of these axes was y = 7.5 mm right above the burner exit.

A coaxial nozzle burner with an inside diameter (d) of 2 mm and an outside diameter of 20 mm was used.<sup>[11]</sup> The fuel was methane, and dry air was used as the oxidizer. A Cartesian coordinate system with the origin located at the center of the burner exit was employed.

Figures 1 (a) and (c) depict the flame inclined asymmetrically with the minimum value of the flame height. Figure 1 (b) depicts the border of the direction of the inclination. It was found<sup>[6]</sup> that the variation in the stable position differed when the leading edge of the flame stood between the node and anti-node positions of the standing wave. The flame height was consistent with the flame height without oscillation. Moreover, the height was reduced when the leading edge of the flame was located between a pressure node and an anti-node of the standing wave. The minimum height was obtained at the center of this width. The stability limit of the lifted jet flame was measured by controlling the airflow velocity (co-flow) at a constant fuel velocity (center flow). The air velocity was increased until the blow-off limit was reached. The blow-off limit with oscillation was determined by the air velocity, which increased with the oscillation until blow-off. The obtained limit was measured as  $V_f = 0.3$  to 4.0 m/s. The jet was moved to various positions between the oscillator and reflector with a standing wave of  $9\lambda/4$ .

The jet trajectory was visualized using acetone PLIF. The preheat zone structure at the leading edge was visualized using acetone-OH simultaneous PLIF. The optics system used for this measurement was the same as in the author's previous work.<sup>[8]</sup> The laser system consisted of a combination of an Nd:YAG (LS-2137, Lotis TII), producing 700 mJ pulses at 1024 nm with a repetition rate of 10 Hz, and a Dye laser (PDL-3, Spectra Physics Inc.). Two excitation lines, 283 nm and 266 nm, were then combined and transformed into a thin sheet by the lens system depicted in the figure. Acetone was added as a tracer of the fuel flow. The fluorescence luminescence profile of this tracer was measured with a CCD camera. The data in this article used the mean value of 100 samples extracted from the pictures or the instantaneous image of the pictures. The average background noise in the images was subtracted from each image in advance. The luminance of the laser sheet was changed along the burner's central axis. We did not attempt to compensate for this non-uniform profile in this work because we compared the images qualitatively. The spatial resolution of each image was 37.8 µm/pixel. Figure 1 indicates the irradiation direction of the laser sheet in the combustion control system. The sphere of this measurement was from y = 19 mm (y/d = 9.5) to the top of the laser sheet  $(y/d \approx 30)$  because the laser sheet interfered with part of the device at the burner exit. The oscillating surface was established in the same direction as in the right-hand side in the image, that is to say, in the negative direction of the x-axis. The axis between the centers of the oscillating and reflecting surfaces corresponded with the irradiation direction of the laser sheet.



Figure 1. Experimental Setup and Flame Photographs

#### 3. Results and Discussion

Figure 2 depicts the variation in the air velocity  $V_a$  of the blow-off limit (B. O.) induced by the oscillation changing in the jet exit position  $x_j$  with a constant fuel velocity of  $V_f = 1.5$  m/s. The jet exit position  $x_j$  is defined as the distance from the oscillator surface to the burner center. The oscillation increased the blow-off limit velocity  $V_a$ . The rate of increase was varied by the jet exit position  $x_j$ . This variation is related to the sound pressure level in the standing wave between the oscillator and the reflector. These tendencies were the same as with other conditions of the fuel velocity  $V_f$ , the results of which do not appear in this article. In short, the oscillation of the standing wave in a high-frequency mode improved the lifted flame stability at all velocities.

Figure 3 presents the variation of the jet angle  $\theta$  induced by the oscillation changing in the jet exit position  $x_j$ . An acetone-PLIF image of the unburned fuel jet is also presented. The image indicates that the fuel jet was bent toward the reflector surface. We defined this case as the positive sign of jet angle  $\theta$ . In contrast, jet angle  $\theta$  was determined to have a negative sign when the fuel jet was bent to the oscillator side. The result indicated that the fuel jet was bent by the oscillation. The bending angle was related to the sound pressure level, and the direction to the distance from the oscillator.

We checked the blow-off limit when the jet axis was inclined without oscillation (triangles in Fig. 2). In this case, the inclined angle of the burner was set to the same value of the jet angle  $\theta$  with oscillation. The blow-off limit of the inclined burner without oscillation was lower than that with oscillation. This indicates that the flame stability with oscillation cannot be explained by only the balance of the burning velocity and bent inflow velocity at the leading edge of the flame. Specifically, there are some sound effects that increase the blow-off limit with oscillation.

Figure 4 presents an acetone-OH simultaneous PLIF image at the leading edge of the lifted flame. Generally, there are some useful flame diagnostics such as CH-PLIF (Planar Laser-induced Fluorescence).<sup>[12]</sup> Nakamura et al.<sup>[9]</sup> proposed a completely different approach to diagnose the premixed flame structure based on the "acetone-OH simultaneous PLIF concept" in 2005. In this scheme, unburned and burned zones are simultaneously visualized by acetone seeded into the fuel flow (unberned zone) and OH generated by combustion (burned zone). We then indirectly track the flame zone sandwiched between them (see the left-hand side of Fig. 4<sup>[9]</sup>). The visualized zone corresponds to the preheat region, so this scheme can readily visualize the local flame structure. The result shows an acetone fluorescence in the lower part of the image. An OH fluorescence can also be





observed in the upper part of the image. Furthermore, a non-luminous region can clearly be seen between these two fluorescence regions.

Figure 5 depicts an increased non-luminous region width  $W_{aceton-OH}$  at the leading edge of the lifted flame just before blow-off with oscillation. Because of the flame stability, the fuel velocity  $V_f$  set 0.5 m/s.  $W_{aceton-OH}$  was measured from 100 images of acetone-OH simultaneous PLIF. Oscillation increased the average  $W_{aceton-OH}$  indicating that the sound affected the flame structure. Our recent work demonstrated that the non-luminous region of acetone-OH simultaneous PLIF was a marker of the preheat zone at the premixed flame edge.<sup>[8]</sup> Therefore, the preheat zone width of the flame at the blow-off limit was increased with oscillation. There is thus some possibility of improving the lean flammability limit using ultrasonic waves.



Figure 4 Acetone-OH simultaneous PLIF image near the flame zone



Figure 5 Expansion of non-luminous region width with oscillation measured with acetone-OH simultaneous PLIF

## 4. Conclusions

Methane-air laminar lifted flame behavior was observed experimentally when excited by a 20 kHz high-frequency oscillation of a standing wave created by a bolt-clamped Langevin transducer and the following conclusions were drawn.

1. The stability near the blow-off limit of a lifted flame is improved.

2. The degree of stability improvement is related to the jet position relative to a standing wave.

3. The standing wave inclines the jet flow. Furthermore, it increases the lean flammability limit.

These sound effects are the reason of above phenomena.

### Acknowledgments

This work was supported by a 2008 grant from Ono Acoustics Research Foundation, a 2009 grant from the Japan Science and Technology Agency, and a 2010 grant from the Iron and Steel Institute of Japan, all of which were executed under the leadership of M.H.. Acetone-OH simultaneous PLIF measurement was supported by a 2008 grant from the General Sekiyu Research & Development Encouragement & Assistance Foundation, a 2008 to 2009 grant from the TEPCO Research Foundation, a 2009 to 2010 grant from the Steel Industry Foundation for the Advancement of Environmental Protection Technology, a 2009 The Iwatani Naoji Foundation's Research Grant, and a 2009 grant from the Research Foundation for Electrotechnology of Chubu (RFEC), all executed under the leadership of Y.N.. The dedicated assistance of Mr. Ito, Mr. Yamada, and Mr. Qomarul was quite helpful. M. H. and Y. N. would like to express their sincere thanks to them for their support in conducting this study.

### References

[1] Hirota, M., Yokomori, T., Yasuda, K., Nagai, Y., Mizomoto, M. and Masuya, G., "Burning Velocity of Triple Flames with Gentle Concentration Gradient", Proceeding of the Combustion Institute, Vol.31, (2007), pp.893-899.

#### Hirota, M.

[2] Hirota, M., Mizomoto, M. and Masuya, G., "Response of Triple Flame to Temporal Chanege in Concentration Gradient", Transactions of the Japan Society of Mechanical Engineers, Series B, Vol.70, No.691, (2004-3), pp.789-795 (in Japanese).

[3] Noda, S., Kamitakahara, Y., Onodera, K., Kamiya, S. and Onuma, Y., "Investigation of the Nearfield Structure of Jet Diffusion Flames by the Laser Sheet Method (2<sup>nd</sup> Report, Mechanism of Flame Stabilization by Speaker Excitation)", Transactions of the Japan Society of Mechanical Engineers, Series B, Vol.64, No.617, (1998-1), pp.283-289 (in Japanese).

[4] Chao, Y. C., Jong, Y. C. and Sheu, H. M., "Helical-mode Excitation of Lifted Flames Using Piezoelectric Actuators", Experiments in Fluids, Vol.28, (2000), pp.11-22.

[5] Kurimoto, N., Suzuki, Y. and Kasagi, N., "Active Contral of Lifted Flames with Arrayed Micro Actuators", Transactions of the Japan Society of Mechanical Engineers, Series B, Vol.71, No.701, (2005-1), pp.191-199 (in Japanese).

[6] Hirota, M., Hashimoto, K., Oso, H. And Masuya, G., "Improvement of Laminar Lifted Flame Stability Excited by High-Frequency Acoustic oscillation", Journal of Thermal Science and Technology, (2009), Vol.4, No.1, pp.169-177.

[7] Kozuka, T., "Non-contact Acoustic Manipulation Using Crossing Ultrasound", Proceeding of World Congress on Ultrasonics 2003, (2003), pp.483-486.

[8] Nakamura, Y., Yamada, Y., Hirota, M., and Saito, T., "Strategy to Diagnose Ultra-lean ( $\phi < 0.6$ ) Premixed Flames by Acetone-OH Simultaneous PLIF with One-laser and One-detector Combination", Journal of Visualization, Vol.14, No.1 (2011), pp.75-84.

[9] Nakamura, Y., Manome, S., Satomi, T., Hayashi, N., and Yamashita, H., "Flame Diagnostics with Acetone-OH Simultaneous PLIF", Journal of Combustion Society of Japan, 47-142, (2005), pp.290-299 (in Japanese).

[10] Nakamura, Y., Manome, S., and Yamashita, H., "Imaging and Diagnostics of Turbulent Methane-Air Premixed Flames by Acetone-OH Simultaneous PLIF", Journal of Visualization, 11-1, (2008), pp.71-78.

[11] Hirota, M., Sekine, K., Hashimoto, K., Saiki, A., Takahashi, H. and Masuya, G., "Measurement of Fuel Concentration Profile at Leading Edge of Lifted Flame with Acetone Laser-Induced Fluorescence", Journal of Thermal Science and Technology, (2009), Vol.4, No.2, pp.238-247.
[12] Kiefer, J., Li, Z. S., Seeger, T., Leipertz, A., and Alden, M., "Planar Laser-induced Fluorescence of HCO for Instantaneous Flame Front Imaging in Hydrocarbon Flames", Proceeding of the

Combustion Institute, Vol.32, (2009), pp.921-928.