Improvement of Laminar Lifted Flame Stability Excited by High-Frequency Acoustic Oscillation*

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Abstract
A high-frequency (20kHz) standing wave was applied to the unburned mixture upstream of a methane-air lifted jet flame using a bolt-clamped Langevin transducer (BLT) to improve stability. The flow field near the flame was visualized using acetone planar-laser-induced fluorescence (PLIF). The standing wave decreased the lifted flame height and increased the blow-off limit. The upstream flow field of the center jet then bent. This phenomenon appeared when there was a density difference between the center jet and the surrounding secondary flow. When the density of the center jet was less than that of the co-flow, the center jet was redirected to the pressure anti-node side. Conversely, when the density of the center jet was greater than that of the co-flow, the center jet was redirected to the pressure node side. This redirection tended to stabilize the laminar lifted flame.

Key words: Premixed Combustion, Lifted Flame, Stability, Supersonic Wave, Sound and Acoustic

1. Introduction

Improving combustion stability using combustion control technology is important to cope with both reducing the load of the environment caused by combustion and raising combustor efficiency. General combustors make use of a jet diffusion flame. When the jet diffusion flame is lifted, the fuel and oxidizer are mixed well, so the nitrogen oxide (NOx) decreases. Unfortunately, a lifted flame is less stable than an attached flame and the lifted flame often blows off. Therefore, it is necessary to control the lifted flame stability.

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. (2) 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. (3) 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 account of 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 controlling the upstream flow velocity. This means that this control influences all of the downstream flow fields. Noda et al.\(^\text{(4)}\) controlled the lifted flame height using loudspeaker oscillation. Chao et al.\(^\text{(5)}\) tried to improve the lifted flame stability using eight piezoelectric actuators around the burner exit, driving them with a phase difference to generate vortices. Kurimoto et al.\(^\text{(6)}\) used flap-like micro-actuators to actively control the lifted flame, producing fluctuations in the shear layer between the inner and outer flow of a coaxial jet. Ogawara et al.\(^\text{(7)}\) used a synthetic jet system driven by a loudspeaker to actively control the lifted flame height. They operated the synthetic jet from the vertical direction to the flow direction. These systems can control the burning conditions, such as flame stability, because of the influence of the fluctuations on the mixing layer at the leading edge of the flame. The frequencies used are within the limits of 10 to 1000Hz\(^\text{(4)-(7)}\) so that the influence of fluctuations extends radially 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. This oscillation has high directionality, since a plane wave and a standing wave are easily formed. There is a lot of considerable research indicating that high-frequency oscillation affects liquids\(^\text{(8)-(10)}\). 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 behavior. In particular, we report evidence of improved stability limits of the lifted flame achieved by reducing the lifted flame height and expanding the blow-off limit, and also indicate the reason for this.

### 2. Experiment setup and method

Figure 1 schematically illustrates the oscillating system used. A bolt-clamped Langevin type transducer was chosen for the oscillator (BLT in Fig. 1, Honda Electronics Co. Ltd., HEC-3020P2B), connected to a handmade horn using a stick screw. The flange part of the horn was anchored with a bolt and nut to the aluminum plate (A1050, 10mm in thickness). A sine-wave voltage was applied between the electrodes of the BLT to generate the oscillation because there is little velocity variation of the oscillating surface when a sine wave is used. A bipolar power supply (Matsusada Precision Inc., HJPZ-0.3P) was used for the oscillator power supply. A function generator (Metex Co. Ltd., MXG-9802A) was used to generate the driving wave. The amplitude and offset were monitored with an oscilloscope (Tektronix Japan Ltd., TDS2022). The oscillating surface was a round shape with a diameter of 15mm. A reflecting surface, also round and with the same diameter and
quality of material as the oscillating surface, was established on the opposite side. The center of the oscillating surface was consistent with the reflecting surface. The frequency (\(\lambda\)) was 20.27kHz, which was near the resonance frequency of this oscillating system. The amplitude was 105V. The fixed distance between the oscillating and reflecting surfaces was 30mm. A standing wave of \(7\lambda/4\) was able to 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 \(y = 7.5\, \text{mm}\) right above the burner exit.

The coaxial nozzle burner was the same as that of Hirota\(^{(11)}\) with an inside diameter (d) of 2mm and an outside diameter of 20mm. Methane was used for the fuel, and dry air was used as the oxidizer. The Cartesian coordinate system was used, with the origin located at the center of the burner exit (Fig. 1).

First, generation of the standing wave was verified with suspended objects in the pressure fluctuation field. There are many results\(^{(8)},\!(12)-(14)\) involving an object suspended at the node of the gaseous pressure field of the standing wave. Vinyl film (4mm square, 0.01mm thickness) was used as the floating object in this work. We were able to qualitatively observe the generation of the standing wave (described in detail in the next chapter). There were some differences between the suspended positions and the theoretical ones due to the effect of gravity, acoustic flow, and so on.

Next, the standing wave was applied to the lifted jet flame. The position of the lifted jet flame was investigated while changing the position of the oscillating system along the x-axis. The lifted flame position was estimated by measuring the lifted flame height (\(H\)) and the distance between the flame center axis and the burner center axis (\(\Delta x\)).

The stability limit of the lifted jet flame was measured by changing the airflow velocity (co-flow) under a constant fuel velocity (center flow). The lifted flame height without oscillation was measured at the beginning. The oscillation was then applied to the lifted flame and the new height was measured. When the flame reattached to the burner rim or blew off, the lifted flame height was recorded as zero or no data, respectively. 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 occurred. In this research, these stability limits were measured as \(V_f = 0.7, 1.4, 2.1, 2.8, 4.2, 5.6,\) and 7.0m/s. The jet flow center was located between the node of \(\lambda\) and the anti-node of \(3\lambda/4\) from the oscillating surface with a standing wave of \(7\lambda/4\).

The jet was visualized using acetone-PLIF to reveal the flow upstream of the lifted flame edge. The optics system used for this measurement was same as in the author's usual work\(^{(11)}\). 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 center axis. Compensation for this non-uniform profile was not attempted in this work because we compared the images qualitatively. The spatial resolution of each image was 37.8\(\mu\)m/pixel. Figure 1 indicates the irradiation direction of the laser sheet in the combustion control system. The sphere of this measurement was from \(y = 19\, \text{mm}\) (\(y/d = 9.5\)) to the top of the laser sheet (\(y/d \geq 30\)) 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.
3. Results and Discussion

3.1 Verifying the standing wave

Figure 2 presents an image of suspended objects in the standing wave. The oscillating surface was at the unrestricted end, while the reflecting surface was at the fixed end. To generate a standing wave, therefore, it was necessary to obtain the distances that represent an odd number of quarter wavelengths, i.e. \((2n-1)\cdot \lambda/4\), in which \(n\) is any integer and \(\lambda\) [m] is the wavelength of the sound wave. The amplitude of this standing wave would reflect the pressure amplitude of the longitudinal wave. To shift the phase of the velocity amplitude by \(\lambda/4\), the position of each node was replaced with that of an anti-node. At least \(\lambda/2\), which was no attach to the oscillating and reflecting surfaces, was obtained to investigate the effects of the standing wave position on the flow fields in this work. Consequently, a distance greater than \(5\lambda/4\) was needed. We established the width from the oscillating to the reflecting surface as 30mm, the same as \(7\lambda/4\) of the standing wave. Consequently, the objects were suspended at the three spots seen in Fig. 2. Each floating position was almost consistent with the theoretical value of the pressure node. The objects were suspended continuously at the same position, with some vibration, while the oscillator was driven. It was confirmed that this oscillating system could generate a standing wave between oscillating and reflecting surfaces in this way.

3.2 Flame behavior with oscillation

Figure 3 (a) illustrates the definition of the lifted flame height used in this work. The lifted flame height \((H)\) was the distance from the burner exit to the leading edge of the flame along the \(y\)-axis, measured directly from the photograph. When the leading edge of the flame had an asymmetrical structure caused by the oscillation, the lifted flame height was defined as the intersection point between the center axis of the flame and the line that links the two sides of the leading-edge point. When the lifted flame was unstable, the lifted flame height was defined as the average value obtained from the twenty photographs. Figure 3 (b) defines the gap distance between the center axis of the burner and the center axis of the flame \((\Delta x_c)\). The flame center is a line parallel with the burner axis, which passes through the mid point between the leading edge points, as
determined from the photograph. The origin is the center of the burner exit, and the gap to the oscillator is defined as positive change.

Figure 4 illustrates the flame stability position as it changes in the oscillating surface location along the burner radius direction, maintaining a constant distance between the oscillating and reflecting surfaces. The values of $H$ and $\Delta x_c$ were normalized by the inner burner diameter $d$ (2mm), resulting in a dimensionless figure. The horizontal axis is $L$, representing the distance from the oscillating surface to the burner center axis. The dotted lines $(\lambda/2, \lambda, 3\lambda/2)$ are at the pressure nodes of the standing wave in Fig. 4. The solid line ($H/d = 24.4$) is the lifted flame height without oscillation, which does not change with $L$. It was found that the variation in the stable position was different when the leading edge of the flame stood between the node and anti-node positions. $H/d$ became maximum at $L = \lambda$ and $3\lambda/4$. This height was almost consistent with the 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. $\Delta x_c/d$ became zero near the node position ($L = \lambda$) or the anti-node position ($L = 3\lambda/4$). There were no variations at that point caused by oscillation because the lifted flame was generated symmetrically along the burner center axis. In contrast, the flame position was shifted along the $x$-axis from the center of the burner when the leading edge of the flame was located in the region between a pressure node and an anti-node. The maximum or minimum in this center region tended to be the same as in the case of $H/d$. The horizontal position of the flame surface moved to the oscillating surface at $L = 3\lambda/4 \sim \lambda$ and to the reflecting surface at $L = \lambda \sim 5\lambda/4$. Specifically, the flame moved in the pressure anti-node direction. Figures 4 (a) and (c) depict the flame inclined asymmetrically with the minimum value of $H/d$. Figure 4 (b) indicates the border of the direction of the inclination.

### 3.3 Variation in the flame stabilization limit

Figure 5 depicts the variation in the lifted flame height and blow-off limit caused by the oscillation changing in air of velocity $V_a$ under a constant fuel velocity $V_f = 1.4\text{m/s}$ at $L = 14\text{mm}$ ($L$ remained constant from this point on). The lifted height $H$ was divided by the inner nozzle exit diameter $d$ for nondimensionalization. The arrows indicate the blow-off limit (B. O.) and the drop-back limit. Furthermore, pairs of direct photographs of the
flame are presented. The left-hand photographs in these pairs did not have the oscillation applied, whereas the right-hand photographs did have the oscillation applied. The lifted flame height was reduced by the oscillation. The photographs indicate that the structure of the leading edge of the flame was inclined asymmetrically with the oscillation. The drop-back occurred below $H/d = 7.5$ (the dotted line), which was the same as the height of the upper end of the oscillating surface. That is to say, flame drop-back occurred when the leading edge of the flame was located inside the oscillation region. The lifted flame height was clearly reduced by the oscillation, increasing in $V_a$ when $H/d > 7.5$. The blow-off limit was also improved by the oscillation. 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 high-frequency mode improved the lifted flame stability at all velocities. However, one has to pay attention to the fact that the flame drop-back occurred under some conditions.

3.4 Variation in the flow field near the oscillating region

Figure 6 presents acetone-PLIF images in which (a) is only the jet without oscillation, (b) is only the jet with oscillation, and (c) is the lifted jet flame with oscillation (the white line indicates the leading edge of the flame). The respective conditions of the fuel and air jet streams were $V_f = 1.4\text{m/s}$ and $V_a = 0.52\text{m/s}$. A stable flow field and flame were obtained in this condition, so the averaged images were adopted. A symmetrical jet flow was generated along the burner center axis without oscillation. In contrast, the jet flow bent toward the oscillating surface with oscillation applied. The leading edge of the flame also became asymmetrical. This variation in the flow direction was a factor in the phenomenon whereby the flame was pulled toward the oscillating surface. The tendency of the inclination of the jet flow direction under other conditions was almost the same, despite the fact that the height of the lifted flame was slightly different.

We believe that the improvement in the flame stability discussed in

![Fig. 5. Lifted height characteristic at $V_f = 1.4\text{m/s}$](image)

![Fig. 6. Averaged acetone-PLIF images (a. Cold flow without excitation. b. Cold flow with excitation. c. Combustion with excitation)](image)
Section 3.3 was due to these inclination effects of the flow. The extent of these effects was evaluated using a simple analysis model. The lifted flame was stable when the burning velocity of the leading edge $S_u$ was the same as the local unburned gas velocity $V$, as seen in Fig. 7 (a). The unburned jet flow and flame were inclined at angles of $\theta$ and $\alpha$, with oscillation applied as in Fig. 7 (b). The local unburned gas velocity $V$ flowing perpendicularly to the flame surface is indicated as $V = V' \cos(\alpha + \theta) = S_u$, assuming that the burning velocity $S_u$ is constant. From this equation, we get the relation $V' = S_u / \cos(\alpha + \theta)$. The velocity along the $y$-axis $V_{\text{local}}$ was indicated as $V_{\text{local}} = V' \cos \theta = S_u \cos \theta / \cos(\alpha + \theta)$, which is greater than $V$. Thus, the flame surface advanced in the upstream direction and stood at a position where the velocity was faster. Based on this simple model, the inclined angle of the unburned jet flow $\theta$ and the angle of the flame $\alpha$ were measured from Fig. 6. The flame incline angle changed linearly with the jet flow angle. Therefore, it was assumed that these angles changed linearly with $V_a$ as seen in Fig. 8 (a). The one-dimensional maximum burning velocity (15) was substituted for $S_u$ in the equation for $V_{\text{local}}$ as mentioned above, with the result seen in Fig. 8 (b). Moreover, it was assumed that $V_{\text{local}}$ decreased linearly from $V_a$ at $H/d = 0$ to the one-dimensional laminar burning velocity at the lifted flame height without oscillation along each line seen in Fig. 9. The value of $V_{\text{local}}$ was obtained for each $V_a$ from Fig. 8 (b), and the intersection points of these values in Fig. 9 (●) indicate the estimated lifted flame height from the angle of the flame. These estimates are plotted as a curved line in Fig. 5. The tendency of this curve was almost the same as the experiment result with the oscillation. Namely, it was indicated that one cause of the improvement in the lifted flame stability was the inclination of the flow fields with the oscillation. We concluded that these values differed because of the approximation of the jet flow velocity decreasing.
3.5 Details of the flow-field inclination

An inclination of the flow field due to the oscillation was observed. The jet flow was bent in the pressure anti-node direction when the center of the jet was located between a pressure node and an anti-node of the standing wave. The decision factor for the bending direction was not clear so this point was investigated as follows.

A recent examination of floating objects with ultrasonic waves (8), (12)−(14) used liquid (water or oil) or solid matter (a sphere of styrene foam) in the air. The objects were suspended at the pressure node in this case. However, the jet flow was bent in the pressure anti-node direction in this work. The density of methane that was used for fuel was 0.717kg/m³ (16), with a specific gravity with respect to air of 0.555, whereas the density of the liquid or solid matter was greater than that of air. That is to say, the relation between the density of the surrounding air and the objects was inverse. We concluded that the inclination direction of the jet flow was decided by the density difference between the center and surrounding flow, and established this with argon gas. The density of argon, which was used in place of methane, was 1.784kg/m³ (16), with a specific gravity with respect to air of 1.38. Figure 10 presents an acetone-PLIF image of the methane or argon flow for \( V_f = 1.4 \text{m/s} \) and \( V_a = 0.52 \text{m/s} \). Each image is an average of 100 images. Only the qualitative differences were compared. The methane jet was bent toward the oscillating surface, which was the pressure anti-node direction. In contrast, the argon jet was bent toward the reflecting surface, which was the pressure node direction. Specifically, the argon jet behaved the same as floating objects in the air because its density was higher than that of air. The above results indicate that the gas with a lower density than the surrounding gas was pulled toward the pressure anti-node direction with the oscillation. That is to say, the inclination of the jet flow occurred with a density difference between the center jet and surrounding gas, with the direction determined by the magnitude. This effect was the same as the heat acoustic-flow effect based on density difference indicated by Tanabe et al. (17)

4. Conclusions

Methane-air laminar lifted flame behavior when excited by a 20kHz high-frequency oscillation of a standing wave created by a bolt-clamped Langevin type transducer was observed experimentally and the following conclusions were drawn.
1. The lifted flame stability is improved.
2. The cause of the above phenomenon is that the area upstream of the leading edge of the flame is inclined by the standing wave.
3. The above effect may be verified when there is a density difference between the center jet and the surrounding flow. In particular, the center jet is inclined toward the pressure anti-node direction when the density of the center jet is lower than that of the surrounding gas.
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References