Response of Stretched Cylindrical Diffusion Flame to Sinusoidal Oscillation of Air Flow Velocity

Yosuke Suenaga¹, Hideki Yanaoka¹, Mamoru Kikuchi¹ and Shun Sasaki²
1. Department of Systems Innovation Science, Iwate University, Morioka 020-8551, Japan
2. Mazda Motor Corporation, Hiroshima 730-8670, Japan

Abstract: An experimental study investigated the characteristics of a stretched cylindrical diffusion flame, with a convex curvature with respect to the air stream, in response to periodic air flow velocity oscillation. The fuel was methane diluted with nitrogen, and the oxidizer air. The oscillation frequency was varied from 5 to 250 Hz. The results are summarized as follows. Though the fluctuation amplitude of the air stream velocity gradient was constant with respect to the frequency, the amplitude of the fuel stream increased. The fluctuation amplitude of the flame radius changed quasi-steadily from 5 to 25 Hz, and decreased with increasing frequency in the frequency range greater than 50 Hz. The flame luminosity did not respond quasi-steadily at 5 Hz, and the oscillation amplitude of flame luminosity was less than that of a steady flame, over the same velocity fluctuation range. The oscillation amplitude of luminosity peaked at 50 Hz, and was greater than that of a steady flame. It is considered that this complex change in flame luminosity with respect to frequency was closely related to the phase difference in the respective time variations in the ratio of flame thickness to radius, the velocity gradients of the air and fuel streams, and the magnitude of these values, with the ratio of flame thickness to radius related to the flame curvature effect, the velocity gradient of the air stream correlated to the flame stretch effect, and the velocity gradient of the fuel stream impacting the fuel transportation.

Key words: Combustion, diffusion flame, velocity oscillation, flame stretch, flame curvature.

1. Introduction

In turbulent combustion, flame shape and flow are subject to unsteady change. To investigate the effect of flow unsteadiness on a flame is important to understand this combustion phenomenon. As basic research on turbulent diffusion flames, there are studies on counterflow flat diffusion flames with a stretch effect attributable to the velocity gradient alone [1-6]. To predict the combustion behavior of a turbulent diffusion flame, it is necessary to understand the influence of velocity fluctuation on a laminar diffusion flame that is simultaneously influenced by stretching and curvature. Using a steady stretched cylindrical diffusion flame, we have experimentally studied the influence of stretch and curvature on flame temperature and extinction [7, 8]. The present study investigated the influence of sinusoidal oscillation of air flow velocity on flame radius and luminosity.

2. Experimental Setup and Procedure

The burner was identical to that used in our studies on steady stretched cylindrical diffusion flames [7, 8]. The coordinate system and flame image are shown in Figs. 1 and 2. The burner consisted of a radial-flow nozzle and a stainless steel tube, 1.2 mm in diameter, installed along the central axis of the nozzle. The nozzle outlet was 10 mm wide and 12 mm in diameter, and the oxidizer flowed toward the central axis. Eight 0.3 mm openings were made, in 11 circumferential lines, at 1 mm intervals in the axial direction, on the stainless steel tube (i.e., the fuel tube) installed along the central axis. The fuel flowed through these openings, in the radial direction. Methane (CH₄) was used as fuel, and air was used as the oxidizer. Nitrogen (N₂) was used to dilute the fuel flow, and the
where \( m \) is the line source rate per unit length from the central axis, \( g \) is the velocity gradient vertical to the flame sheet, and \( \rho \) is the density. When \( v_a \) is oscillated, the stagnation point \( r = R_a \) is moved with velocity \( dR_a/dt \). Since the cylindrical flame in this study was formed near the stagnation surface, we assumed that \( R_a \) and \( dR_a/dt \) were equal to \( r_f \) and \( dr_f/dt \), respectively, where \( r_f \) is the flame radius. Substituting into Eq. (1) the velocity \( v_r = -v_a \) at the outlet of the nozzle \( r = R_a \) and the moving velocity \( v_r = dr_f/dt \) at the stagnation surface \( r = R_f \) (= \( r_f \)), the velocity gradient \( g_a \) of the air flow was obtained as Eq. (2):

\[
g_a = \frac{r_f \frac{dr_f}{dt} + R_o v_a}{R_o^2 - r_f^2}
\]

Substituting into Eq. (1) the velocity \( v_r = v_f \) at the outlet of the fuel tube \( r = R_f \), and the moving velocity \( v_r = dr_f/dt \) at the stagnation surface \( r = R_f \) (= \( r_f \)), the velocity gradient \( g_f \) of the fuel flow was obtained as Eq. (3):

\[
g_f = \frac{r_f \frac{dr_f}{dt} - R_v v_f}{R_v^2 - r_f^2}
\]

Hereafter, the steady flame and flame with velocity oscillation are called the static flame and dynamic flame, respectively.

The flame radius \( r_f \), flame thickness \( \delta \), and flame luminosity \( L_f \) were determined by analyzing images taken with a high speed video camera (Phantom v1210, Vision Research Inc., USA). The spatial resolution of the photographed images was 0.03 mm/pixel. \( r_f \) was determined as the position at the maximum value \( L_{f,max} \) in the radial luminosity distribution. \( \delta \) was defined as the width \((= \delta_{out} - \delta_{in})\) of the half value of \( L_{f,max} \) obtained from the radial distribution of luminosity. \( L_f \) was obtained by dividing the integrated value of the luminosity from \( \delta_{out} \) to \( \delta_{in} \) by \( \delta \). All the dynamic flame results in this paper are phase-averaged values of the results for 20 cycles.
3. Experimental Results and Discussion

3.1 Frequency Characteristics of the Velocity Gradients of the Fuel and Air Flow

In Fig. 3, the horizontal and vertical axes represent the velocity gradients of the air and fuel stream, \( g_a \) and \( g_f \), respectively. The velocity oscillation frequencies \( f \) were 5, 50, and 250 Hz. For comparison, the relation between \( g_a \) and \( g_f \) for the static flame is also shown in Fig. 3. We can see that the curve at 5 Hz varies in the same manner as that of the static flame, and that \( g_f \) fluctuates quasi-steadily with varying \( g_a \). However, when \( f \) increases to 50 Hz, the curve deviates from the static flame curve, and when \( f \) increases to 250 Hz, the curve deviates greatly from that curve. Though the fluctuation width of \( g_a \) is constant regardless of \( f \), the fluctuation width of \( g_f \) increases with increasing \( f \). These results suggest that when the air flow velocity alone is changed sinusoidally, the fluctuation amplitude of \( g_a \) is constant, while the amplitude of \( g_f \) increases with increasing \( f \).

3.2 Frequency Characteristics of the Flame Radius

As the flame is formed on the air stream side of the stagnation surface, variation in the flame radius as a function of the velocity gradient of the air stream was also investigated, and the results are shown in Fig. 4, where \( r_f \) and \( g_a \) are the flame radius and the velocity gradient of the air stream, respectively. For comparison, the static flame results are also shown in Fig. 4. We can see that, at 5 Hz, \( r_f \) varies in the same manner as that of the static flame, while at 250 Hz, \( r_f \) remains almost constant.

Fig. 5 shows the frequency characteristics of the fluctuation amplitude ratio of the flame radius \( \Delta R (=\Delta r_f \text{dyn}/\Delta r_f \text{stat}) \), with \( \Delta r_f \text{dyn} \) and \( \Delta r_f \text{stat} \) being the respective amplitudes of the dynamic and static flame radii, over the same air velocity range. In the range of 5 to 25 Hz, \( \Delta R \) is almost unity, and we can see that the flame radius responds quasi-steadily. When \( f \) is greater than 50 Hz, however, \( \Delta R \) is reduced. This tendency is
similar to the response characteristics of the counterflow flat diffusion flame, with simultaneous sinusoidal fluctuation in the fuel and air flow velocities [1]. These results suggest that the flame radius responds quasi-steadily in the low frequency range, but the response characteristics become unsteady in the high frequency range.

3.3 Frequency Characteristics of the Ratio of Flame Thickness to Flame Radius

The influence of flame curvature on the combustion characteristics of the cylindrical flame becomes notably significant as the ratio of the flame thickness to the flame radius (= $\delta/r_f$) increases [9]. Fig. 6 shows the change in $\delta/r_f$ as a function of the velocity gradient of the air flow $g_a$. For comparison, the static flame results are also shown in Fig. 6. The $\delta/r_f$ curves form ellipses at all $f$, however they otherwise differ significantly with differing $f$. In general, when $f$ is low, the flame is considered to respond quasi-steadily. However, at 5 Hz, $\delta/r_f$ does not vary in the same manner as that of the static flame; the $\delta/r_f$ of the dynamic flame is greater than that of the static flame when $g_a$ is large. In addition, the maximum value of the $\delta/r_f$ of the dynamic flame is clearly greater than that of the static flame in this study. On the other hand, the $\delta/r_f$ of the dynamic flame almost equals that of the static flame when $g_a$ is small. At 50 Hz, the change in $\delta/r_f$ is nearer to the static flame curve than at 5 Hz, and $\delta/r_f$ at 250 Hz is greater than the static flame curve when $g_a$ is large. These results suggest that the influence of flame curvature does not produce quasi-steady behavior in the low frequency range, because there is a slight phase difference between the flame radius and flame thickness.

3.4 Frequency Characteristics of the Flame Luminosity

Fig. 7 shows the change in flame luminosity $L_f$ as a function of the velocity gradient of the air stream $g_a$ at 5, 50, and 250 Hz. For comparison, the $L_f$ of the static flame is also shown in Fig. 7. We can see that the $L_f$ at 5 Hz does not vary in the same manner as that of the static flame, and the variation is not quasi-steady, that is, while the $L_f$ of the dynamic flame is almost equal to that of the static flame when $g_a$ is small, it is less than that of the static flame when $g_a$ is large. Therefore, the fluctuation width of the dynamic flame $L_f$ with changing $g_a$ is less than that of the static flame. When $f$ increases to 50 Hz, the fluctuation width becomes large with changing $g_a$. However, the fluctuation width at 250 Hz is less than that of the static flame.

Fig. 8 shows the frequency characteristics of the fluctuation amplitude ratio of the flame luminosity $\Delta L$ ($= \Delta L_{f,dy}/\Delta L_{f,st}$). $\Delta L_{f,dy}$ and $\Delta L_{f,st}$ are the respective
amplitudes of the dynamic and static flame luminosities, over the same air velocity range. $\Delta L$ at 5 Hz is less than unity, regardless of the low frequency, and increases with increasing $f$ until, at 50 Hz, it is larger than unity and reaching a maximum. Then $\Delta L$ decreases with respect to $f$, becoming less than unity when $f$ exceeds 150 Hz.

The fact that $\Delta L$ becomes less than unity at 5 Hz that is related to the influence of flame curvature, as shown in Fig. 6. In our study on steady stretched cylindrical diffusion flames, which was conducted under the same experimental conditions, the flame temperature decreased with increasing flame curvature (that is, the flame was weakened). In contrast, the flame temperature increased with an increase in the flame stretch rate (that is, the flame was strengthened) [8]. The flame stretch rate is proportional to the velocity gradient. In the previous section, it was shown that, at 5 Hz, $\delta/r_f$ is larger than that of the static flame when $g_a$ is large. In this region of large $g_a$, it is considered that the effect of weakening the flame due to the increase in $\delta/r_f$ was more significant than the effect of strengthening the flame due to the increase in $g_a$. Therefore, as shown in Fig. 7, when $g_a$ was large, the $L_f$ of the dynamic flame became less than that of the static flame. As a result, the fluctuation width of $L_f$ at 5 Hz was less than that of the static flame, and $\Delta L$ became less than unity.

Next, we will discuss the results at 50 Hz. As shown in Fig. 6, since the change in the $\delta/r_f$ curve at 50 Hz is closer to the static flame curve than at 5 Hz, the flame curvature effect at 50 Hz is considered to be similar to that of the static flame. However, $\Delta L$ is greater than unity. In Fig. 3, it was shown that while the fluctuation amplitude of $g_a$, $\Delta g_a$, is constant regardless of $f$, the amplitude of $g_f$, $\Delta g_f$, increases with increasing $f$. The increasing $\Delta g_f$ increases the fluctuation width of the diffusion layer thickness. As the fluctuation amplitude of the inflow mass flux of the fuel into the flame increases with increasing $\Delta g_f$, it is considered that the fluctuation amplitude of $L_f$ becomes greater than that of the static flame, over the same air flow velocity range. Therefore, $\Delta L$ becomes greater than unity. $\Delta L$ becomes less than unity at 250 Hz because a further increase in frequency attenuates the fluctuation amplitude of the mass flux within the diffusion layer.

4. Conclusions

An experimental study investigated the characteristics of a stretched cylindrical diffusion flame, which had a convex curvature with respect to the air stream, in response to periodic air flow velocity oscillation. The fuel was methane diluted with nitrogen, and the oxidizer air. The oscillation frequency $f$ was varied from 5 to 250 Hz. The flame radius $r_f$, flame thickness $\delta$, and flame luminosity $L_f$ were measured, and the velocity gradients of the air and fuel stream, $g_a$ and $g_f$, were calculated. The results indicated that Eq. (1) though the fluctuation amplitude of $g_a$ was constant with respect to $f$, the amplitude of $g_f$ increased, Eq. (2) the fluctuation amplitude of $r_f$ changed quasi-steadily from 5 to 25 Hz, decreasing with increasing $f$ in the frequency range greater than 50 Hz, Eq. (3) $L_f$ did not respond quasi-steadily at 5 Hz, and the oscillation amplitude of $L_f$ was less than that of a static flame, over the same velocity fluctuation range; the amplitude peaked at 50 Hz, and
was greater than that of a static flame, and Eq. (4) it is considered that this complex change in the flame luminosity with respect to $f$ was closely related to the phase difference in the respective time variations in $\delta r_f/\omega f$, $g_a$, and $g_f$, and the magnitude of these values; with $\delta r_f$ related to the flame curvature effect, $g_a$ correlated to the flame stretch effect, and $g_f$ impacting the fuel transportation.

References


