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

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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 out through these openings, in the radial direction. Methane (CH_4) was used as fuel, and air was used as the oxidizer. Nitrogen (N_2) was used to dilute the fuel flow, and the

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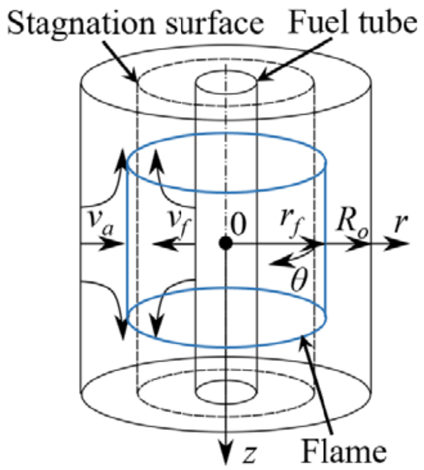

Fig. 1 Coordinate system.

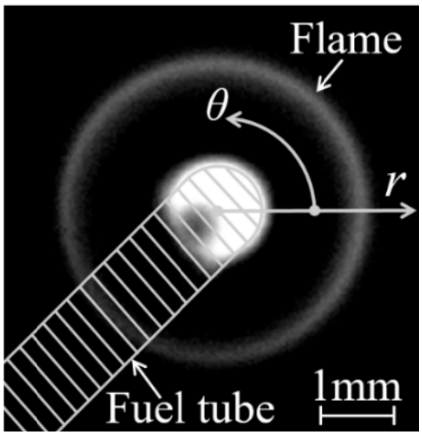

Fig. 2 Flame image.

dilution rate was 50%. As the cylindrical flame was formed in the air flow, the air flow velocity was oscillated sinusoidally using 4 speakers. The fuel flow velocity at the fuel tube outlet, v_f, was maintained at 40 cm/s, and v_a was varied according to $v_a = v_{a,m} + A\sin(2\pi ft)$, where $v_{a,m}$ and A are the mean air velocity and velocity fluctuation amplitude, respectively. In this study, $v_{a,m}$ and A were 40 cm/s and 10 cm/s, respectively, and the velocity fluctuation frequency ranged from 5 Hz to 250 Hz. The oscillating velocity at the radial flow nozzle outlet was measured by PIV (particle image velocimetry). For a radial distance from the centre, and a flow field approximated as a potential flow, the radial velocity v_r is given as follows:

$$v_r = -g \cdot r + \frac{m}{2\pi \rho r} \tag{1}$$

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 ρ is the density. When v_a is oscillated, the stagnation point $r = R_{st}$ is moved with velocity dR_{st}/dt. Since the cylindrical flame in this study was formed near the stagnation surface, we assumed that R_{st} and dR_{st}/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 $r = R_o$, and the moving velocity $v_r = dr_f/dt$ at the stagnation surface$r = R_{st}$ (= r_f), the velocity gradient g_a of the air flow was obtained as Eq. (2):

$$g_a = \frac{r_f \dfrac{dr_f}{dt} + R_o v_a}{R_o^2 - r_f^2} \tag{2}$$

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

$$g_f = \frac{r_f \dfrac{dr_f}{dt} - R_i v_f}{R_i^2 - r_f^2} \tag{3}$$

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 δ, 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. δ 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 δ_{out} to δ_{in} by δ. 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 ΔR (= $\Delta r_{f,dy}/\Delta r_{f,st}$), with $\Delta r_{f,dy}$ and $\Delta r_{f,st}$ 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, ΔR is almost unity, and we can see that the flame radius responds quasi-steadily. When f is greater than 50 Hz, however, ΔR is reduced. This tendency is

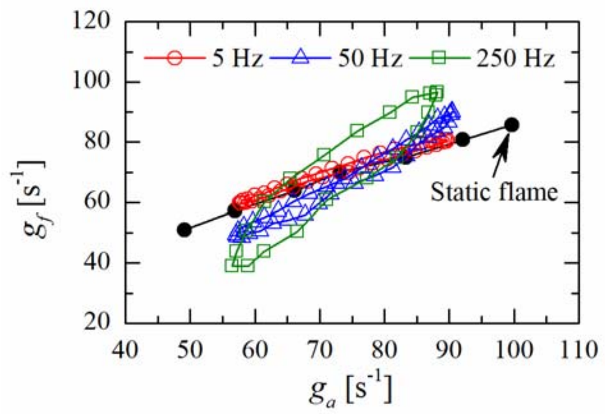

Fig. 3 Dynamic response of the velocity gradient of the fuel stream g_f as a function of the velocity gradient of the air stream g_a, at various frequencies.

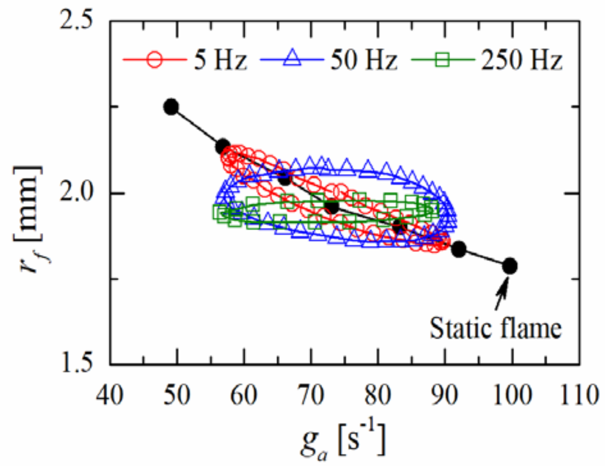

Fig. 4 Dynamic response of the flame radius r_f as a function of the velocity gradient of the air stream g_a, at various frequencies.

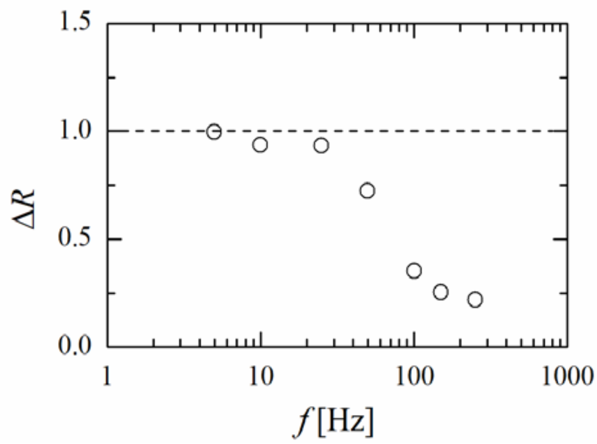

Fig. 5 Frequency characteristics of the oscillation amplitude ratio of the flame radius ΔR (= $\Delta r_{f,dy}/\Delta r_{f,st}$). $\Delta r_{f,dy}$ and $\Delta r_{f,st}$ are the oscillation amplitudes of the dynamic and static flame radii, respectively.

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 (= δ/r_f) increases [9]. Fig. 6 shows the change in δ/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 δ/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, δ/r_f does not vary in the same manner as that of the static flame; the δ/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 δ/r_f of the dynamic flame is clearly greater than that of the static flame in this study. On the other hand, the δ/r_f of the dynamic flame almost equals that of the static flame when g_a is small. At 50 Hz, the change in δ/r_f is nearer to the static flame curve than at 5 Hz, and δ/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 ΔL (= $\Delta L_{f,dy}/\Delta L_{f,st}$). $\Delta L_{f,dy}$ and $\Delta L_{f,st}$ are the respective

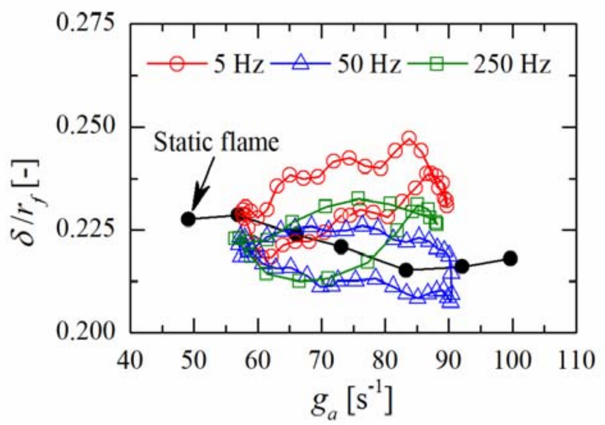

Fig. 6 Dynamic response of the ratio of flame thickness δ to flame radius r_f as a function of the velocity gradient of the air stream g_a, at various frequencies. δ/r_f is associated with the flame curvature effect.

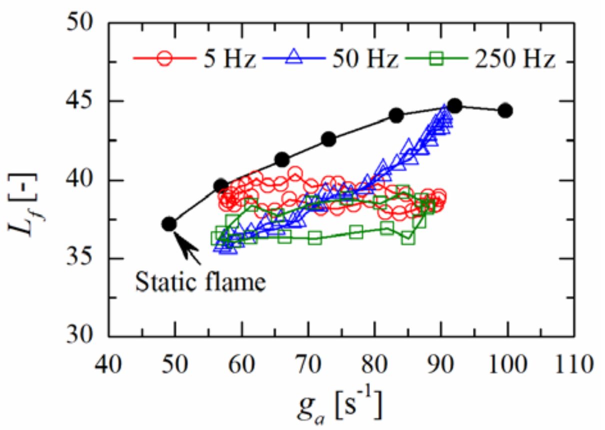

Fig. 7 Dynamic response of the flame luminosity L_f as a function of the velocity gradient of the air stream g_a, at various frequencies.

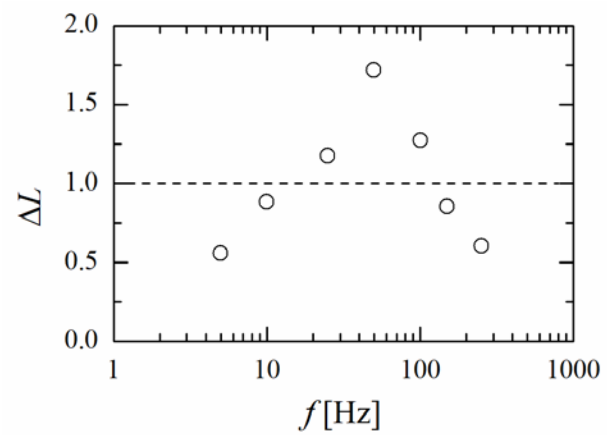

Fig. 8 Frequency characteristics of the oscillation amplitude of the ratio of flame luminosity ΔL (= $\Delta L_{f,dy}/\Delta L_{f,st}$). $\Delta L_{f,dy}$ and $\Delta L_{f,st}$ are the amplitudes of the dynamic and static flame luminosities, respectively.

amplitudes of the dynamic and static flame luminosities, over the same air velocity range. ΔL 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 ΔL decreases with respect to f, becoming less than unity when f exceeds 150 Hz.

The fact that ΔL 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, δ/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 δ/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 ΔL became less than unity.

Next, we will discuss the results at 50 Hz. As shown in Fig. 6, since the change in the δ/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, ΔL is greater than unity. In Fig. 3, it was shown that while the fluctuation amplitude of g_a, Δg_a, is constant regardless of f, the amplitude of g_f, Δg_f, increases with increasing f. The increasing Δg_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 Δg_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, ΔL becomes greater than unity. ΔL 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 δ, 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 δ/r_f, g_a, and g_f, and the magnitude of these values; with δ/r_f related to the flame curvature effect, g_a correlated to the flame stretch effect, and g_f impacting the fuel transportation.

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