Dynamic response of wall-stagnating lean methane-air premixed flame to equivalence ratio oscillation

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Abstract
In order to clarify the response characteristics of a lean methane–air premixed flame to equivalence ratio oscillation from actual measured values of the burning velocity, we developed a new burner with a wall–stagnating flow that allowed measurement of the flow field by using particle image velocimetry (PIV). To create fluctuations in the equivalence ratio only in the direction of flow without varying the velocity field, fuel and air flow rates were controlled by alternately vibrating two sets of loudspeakers. Burning velocity \( Su \) was calculated from the measured unburnt gas velocity \( u_g \) and flame moving velocity \( u_f \) at the front edge of the flame was measured by PIV. \( u_f \) was obtained using a high-speed video camera. For an oscillation with a mean equivalence ratio of 0.85, amplitude of 0.05 and frequency \( f \) ranging from 5 to 50 Hz, the following results were obtained: (1) The oscillation amplitude of the flame position changed quasi–steadily in the low frequency range, decreasing with increasing \( f \) in the frequency range greater than 40 Hz. (2) The oscillation amplitude of the burning velocity of dynamic flame \( \Delta Su_d \) obtained by PIV measurement increased with respect to \( f \), and reached maximum at 40 Hz. The maximum value became greater than that of the static flame \( \Delta Su_s \), over the same equivalence ratio range. This tendency was similar to the result obtained by approximating the flow field by a potential flow. (3) The frequency characteristics of the oscillation amplitude ratio of the burning velocity \( \Delta S \) (= \( \Delta Su_d/\Delta Su_s \)) qualitatively correspond to the results \( \Delta S(p) \) (= \( \Delta Su_{d(p)}/\Delta Su_{s(p)} \)) obtained by approximating the flow field by the potential flow. However, \( \Delta S \) is quantitatively larger than \( \Delta S(p) \), and the difference between \( \Delta S \) and \( \Delta S(p) \) is large in the high frequency range. This is because the approximation of the flow field by the potential flow underestimates the oscillation amplitude of the unburnt gas velocity, and the degree of the underestimation becomes noticeable in the high frequency range.

Keywords: Combustion, Premixed flame, Concentration oscillation, Stagnation flow, Burning velocity

1. Introduction
A stratified combustion gasoline engine has been developed to clean exhaust gas and reduce fuel consumption (Zhao et al., 1999). In a rocket engine and a gas turbine combustor, oscillating combustion occurs due to fluctuations in fuel flow rate (Lefebvre and Ballal, 2010). In such a combustion field, the flame propagates through a mixture of non-uniform concentrations. The characteristics of a flame propagating in a non-uniform concentration field change over time. This dynamic effect produces characteristics that are not in a flame propagating through a homogeneous mixture. In order to improve the performance of the combustor, it is important to understand the dynamic characteristics of a flame propagating in a non-uniform concentration field. The above combustion phenomenon in the engine involves a non-uniform fuel concentration and strong turbulence and thus is very complex. For this reason, a
simple concentration field and flow field are used to determine the effect of the non-uniformity of the concentration and the unsteadiness of the flow. Simple flow fields include a one-dimensional flow, such as in a cylinder, a counterflow, and a wall stagnation flow. A simple non-uniform concentration field can be a field in which the fuel concentration in the mixture entering the flame is changed occasionally or periodically. Cruz et al. (2000) performed a numerical analysis of a laminar flame propagating through a stratified mixture and a homogeneous mixture. They showed that the propagation velocity of a flame propagating through a mixture with the equivalence ratio changing from stoichiometric to lean or from rich to stoichiometric is greater than that of a flame propagating through a homogeneous mixture with the corresponding equivalence ratio and that a flame with the equivalence ratio changing from stoichiometric to rich exhibits the opposite tendency. Marzouk et al. (2000) studied numerically how the flame structure and the burning velocity are affected when the equivalence ratio for a stretched flame in a stagnation flow is occasionally changed from stoichiometric to lean. The study showed that unlike in a homogeneous mixture, a flame propagating through a mixture with an equivalence ratio gradient continues to burn at an equivalence ratio below the lean flammability limit due to the back support effect of heat and radicals from the back side of the flame, and that with the increase in the equivalence ratio gradient, the flame inertia effect is enhanced. Lauverge and Egolfopoulos (2000) performed a numerical analysis of the response of a counterflow premixed flame to sinusoidal fluctuations in the mixture concentration and indicated the presence of a cut-off frequency. Sankaran and Im (2002) studied numerically the effect of sinusoidal fluctuations in the mixture concentration on a counterflow premixed flame as well. They showed that if the mean equivalence ratio of a mixture subjected to concentration fluctuations is higher than that of the lean flammability limit for a steady flame (a static flame), the lean flammability limit for a dynamic flame is lower than that for a static flame, and that as the mean equivalence ratio of the mixture approaches the lean flammability limit for the static flame, the lean flammability limit for the dynamic flame approaches that for the static flame. Numerical studies similar to those described above have been conducted to determine in detail the effect of the non-uniformity of the concentration on the flame propagation velocity (Richardson et al., 2010; Rahman et al., 2012; Zhou and Hochgreb, 2013; Miyamae et al., 2014; Shi et al., 2016; Zhang and Abraham, 2016).

Experimental studies with a stagnation flow were conducted by the authors (Suenaga et al., 2003a, 2003b, 2005, 2007, 2010; Takahashi et al., 2005, 2006) and Tomita et al. (2015). The authors studied the response of a stretched flat premixed flame formed in a wall stagnation flow and a stretched cylindrical premixed flame formed in a porous metal cylinder to periodic concentration fluctuations. The authors caused concentration fluctuations by alternately opening and closing two solenoid valves. In these studies, it was found that the fluctuation amplitude of the burning velocity of a dynamic flame is independent of the flame shape and greater than that of a static flame, over the same equivalence ratio fluctuation range. However, as the burning velocity was obtained by approximating the flow field by a potential flow, the fluctuation amplitude of the dynamic flame might be overestimated. So the burning velocity needs to be evaluated with measurements of the gas velocity to determine the response characteristics of a flame with fluctuating concentrations. In this study, we developed a new burner that allowed measurement of the flow field by using particle image velocimetry (PIV), and the response of a flat premixed flame formed in a wall stagnation flow was investigated experimentally when the mixture concentration was oscillated sinusoidally without the fluctuation in mixture velocity by using two sets of loudspeakers. The burning velocity of the flat static and dynamic flame was determined by PIV, and these combustion characteristics were revealed. In our previous studies (Suenaga et al., 2003a, 2003b, 2005), the combustion characteristics of the dynamic flame have been presented using the burning velocity $S\theta(p)$ obtained by approximating the flow field by the potential flow. Thus, $S\theta(p)$ was also evaluated in this study, and the similarities and differences from the PIV measurement results were also clarified.

2. Experimental setup and procedure
2.1 Burner and mixture supply system

Figure 1 is a schematic of the burner. Figure 2 is a schematic of the mixture supply system and the mixture concentration measurement system. To allow tracer particles to be supplied, the existing burner (Suenaga et al., 2003a, 2003b, 2005) was improved. The burner has also been devised so that fluctuations in the concentration (equivalence ratio) of the mixture are caused only in the direction of the main flow. The burner consists of a mixing chamber and a settling chamber. In the burner, there is a throttle, a perforated plate and metal meshes (40 Mesh: 7; 20 Mesh: 3). The mixture (main flow mixture) at a constant concentration and flow rate, which was formed upstream by mixing the
primary fuel and the primary air well, was supplied to the mixing chamber. In addition, the secondary fuel and the secondary air were supplied at the same average flow rate. To fluctuate the mixture concentration sinusoidally, the flow rates of the secondary fuel and the secondary air were oscillated alternately by using two sets of loudspeakers. And then, the mixture was introduced into the settling chamber to achieve a uniform velocity distribution in the radial direction and was supplied into the combustion field from the outlet with an inner diameter of 20 mm. This makes it possible to cause fluctuations only in the equivalence ratio with the velocity at the outlet of the burner kept constant. In order to prevent the flame interacting with the surrounding air, nitrogen was supplied from the area around the burner outlet. A flat flame formed parallel to a ceramic stagnation wall (SN240, Kyosera Corporation) at a distance $L = 20$ mm from the burner. Two sinusoidal signals were generated from the PC to drive the loudspeakers. The phase difference between the two sinusoidal signals was a half cycle. The amplitude of the equivalence ratio of the mixture at the outlet
of the burner was controlled by amplifying the signals with an amplifier. The frequency $f$ of the concentration fluctuations was controlled by changing the frequency of the signals to the loudspeakers. In the experiment, the mixture flow velocity $U$ was 120 cm/s. $f$ was varied from 5 to 50 Hz. Let $\phi_m$ be the mean equivalence ratio and $A$ to be the equivalence ratio amplitude. The equivalence ratio $\phi$ at the outlet of the burner is given by

$$\phi = \phi_m + A \sin(2\pi f t).$$

In this study, $\phi_m = 0.85$ and $A = 0.05$. Methane (CH$_4$) was used as the fuel and air was used as an oxidizer.

2.2 Method of mixture concentration measurement

3.39 μm infrared absorption spectroscopy was used to measure the mixture concentration in the center of the outlet of the burner (Yoshiyama et al., 1996). Figure 2 shows the concentration measurement system. The laser beam was chopped by a chopper into about 1200 Hz intermittent light and focused by a collecting lens to a 0.2 mm diameter spot that passed through the center of the outlet of the burner. The intermittent light passing through the mixture is detected by a PbSe photoconductive cell via a bandpass filter with a central wavelength of 3.39 μm and converted into an electrical signal. The electrical signal was amplified by a preamplifier and sent to the PC. The data was obtained at a frequency of 25000 Hz under all conditions. Figure 3 shows the time variation of the equivalence ratio at $f = 5$, 20, and 50 Hz that was measured at the outlet of the burner. All dynamic flame results in this paper are phase-averaged values of the results for 20 cycles. In Fig. 3, the horizontal axis represents non-dimensional time $t/T$, where $t$ and $T$ are the real time and the time of one cycle. These figures show that the equivalence ratio $\phi$ fluctuated almost sinusoidally at the outlet of the burner.

2.3 Method of flow field measurement

A high-speed video camera (Phantom V1210, Vision Research Inc., USA) was used for flow field measurement. The recording speed was 9000 FPS under all conditions and the spatial resolution was 35 μm/pixel. Magnesium oxide particles with a nominal size of 1 μm were used as the tracer. In the flow field used, the maximum value of Stokes number of the tracer was $6.8 \times 10^{-4}$. This indicates that the tracer follows the flow well. A DPSS laser beam with a wavelength of 532 nm and an output power of 2 W was used to visualize the flow field. The laser beam was converted by a cylindrical lens into a 1-mm thick laser sheet and directed through the center of the outlet of the burner. The velocity of the flow field was analyzed from the recorded images. The flow field was analyzed by the direct cross-correlation method using analysis software (FlowExpert 2D2C, KATO KOKEN Co., Ltd., Japan).

2.4 Method of flame position measurement

The camera used for PIV measurement was used to measure the flame position. To capture a chemiluminescent emission of CH emitted from the flame, a band pass filter with the central wavelength of 430 nm was installed in the camera lens. The recording conditions were the same as those previously described except that the recording speed was
1000 FPS. The flame was formed parallel to the stagnation wall. The flame position was obtained by MATLAB as follows. Due to the 10-mm radius of the outlet of the burner, the coordinate \( x_f \) that gives the maximum CH radical level was searched for within a radius of \( r = 10 \text{ mm} \) at a spacing of 1 pixel (\( = 35 \text{ μm} \)) in the radial direction. The flame position \( x_f \) was defined as the distance from the average value of \( x_f \) to the stagnation wall.

2.5 Method of evaluation of the burning velocity

An \( x \)-axis that has its origin in the center of the stagnation wall and is positive in the upstream direction is selected. The gas velocity \( |u| \) in the \( x \)-direction is the average value of the velocity obtained within a radius of \( r = 10 \text{ mm} \). Figure 4 is an example of a gas velocity \( |u| \) distribution across a flame in the direction of the \( x \)-axis. The mixture is supplied from the right side in this figure. As in the previous study, as the distance to the stagnation wall decreases, \( |u| \) decreases but is accelerated once due to the thermal expansion of the gas caused by the flame (Law, et al., 1986). There is a flame near the maximum value of \( |u| \). As in the previous study, the unburnt gas velocity \( u_g \) in a stagnation flow flame was defined as the minimum value of \( |u| \) in the immediate vicinity of the flame front. Let the distance from the stagnation wall to the flame \( x \) be equal to \( x_f \) and \( u_f \) be the flame moving velocity. The burning velocity \( S_u \) is defined by

\[
S_u = u_f + u_g
\]

where, for \( u_f = \frac{dx}{dt} \), \( u_f > 0 \) when the flame moves upstream and \( u_f < 0 \) when the flame moves downstream. The flame position data \( x_f \) of 1/5 cycle before and after at each time point was approximated to a quadratic expression by the least squares method, and \( u_f \) was obtained by differentiating the approximate expression with respect to time. \( u_g \) in the potential flow is given by

\[
u_g = \varepsilon \cdot x_f
\]

where \( \varepsilon (= U/L) \) is the stretch rate; \( U (= 120 \text{ cm/s}) \) is the gas velocity at the outlet of the burner; and \( L (= 2 \text{ cm}) \) is the distance from the outlet of the burner to the stagnation wall. In the following, the subscript ‘(p)’ is added to the quantities obtained by approximating the flow field by the potential flow.

3. Results and discussion

In this study, the same average flow rate was set for both the secondary fuel and the secondary air to keep the mixture velocity at the outlet of the burner constant. The effect of the vibration of loudspeakers on the variations of the equivalence ratio \( \phi \), flame position \( x_f \), and unburnt gas velocity \( u_g \) was examined by replacing the secondary fuel with the air. As with the experimental conditions in this study, the mean equivalence ratio \( \phi_m \) was set to 0.85 for each frequency \( f \). Two sets of loudspeakers were controlled to a value that gives the amplitude of the equivalence ratio \( A = 0.05 \) for each \( f \).

Fig. 5 Standard deviations of the equivalence ratio, $\phi_{\text{rms}}$, flame position, $x_{f\text{rms}}$, and unburnt gas velocity, $u_{g\text{rms}}$.

Fig. 6 Dependences of the flame position $x_f$, burning velocities $S_u$ and $S_{u(p)}$ on the equivalence ratio $\phi$ for the static flame in the mixture flow of constant concentration. Here, $S_u$ was obtained by using PIV, and $S_{u(p)}$ was estimated by approximating the flow field by the potential flow.

Figure 5 shows the standard deviations of the $\phi$, $x_f$, and $u_g$ which are the $\phi_{\text{rms}}$, $x_{f\text{rms}}$, and $u_{g\text{rms}}$, respectively. $\phi_{\text{rms}}$ was maximum at 5 Hz and was 0.004. And it is found that $\phi_{\text{rms}}$ decreases with an increase in $f$. $x_{f\text{rms}}$ was constant regardless of $f$ and equal to 0.02 mm. $u_{g\text{rms}}$ was 1.4 cm/s maximum at 5 Hz, decreasing with increasing $f$. The relative uncertainties of $\phi$, $x$, $u_g$ are 0.5%, 0.3%, and 3.8%, respectively. These results indicate that the influence of the vibration of loudspeakers on the variations of the $\phi$, $x_f$, and $u_g$ is small.

3.1 Static flame

The dependences of flame position $x_f$ and burning velocities $S_u$ and $S_{u(p)}$ on the equivalence ratio $\phi$ for the static flame in the mixture flow of constant concentration are shown in Fig. 6. Here, $S_u$ means the burning velocity obtained by PIV measurements, and $S_{u(p)}$ is that obtained by approximating the flow field by the potential flow. From Fig. 6, it is found that $x_f$ increases linearly with increasing $\phi$. $S_u$ and $S_{u(p)}$ also increase with an increase in $\phi$, these values are almost equal at $\phi = 0.85$, which is equal to the mean equivalence ratio $\phi_m$ for the dynamic flame. But, it is found that a variation width of $S_u$ with changing $\phi$ is smaller than that of $S_{u(p)}$. These results suggest that the variations of $S_u$ and $S_{u(p)}$ with respect to $\phi$ agree qualitatively but are different quantitatively.
3.2 Time variations of flame position and moving speed

Figure 7 shows the time variations of the flame position $x_f$. The horizontal axis is non-dimensional time $t/T$. $t$ is thereal time and $T$ is the time of one cycle. It is found that the fluctuation amplitudes of $x_f$ at 5 Hz and 20 Hz are almost equal, and the amplitude at 50 Hz is smaller than those at 5 Hz and 20 Hz.

Figure 8 shows the frequency characteristics of the oscillation amplitude ratio of the flame position $\Delta X (=\Delta x_f/\Delta x_s)$. $\Delta x_d$ and $\Delta x_s$ are the oscillation amplitudes of dynamic and static flame positions, respectively. $\Delta X$ is almost unity ranging from 5 to 20 Hz, decreasing with increasing $f$ in the
frequency range greater than 40 Hz. This tendency is similar to the results of Tomita et al. (2015). These results suggest that the flame position responds quasi-steadily in the low frequency range, but unsteadily in the high frequency range.

Figure 9 shows the time variations of the flame moving velocity $u_f$. The figure shows that in response to the cyclic fluctuations in $\phi$, $u_f$ changes and the fluctuation amplitude in $u_f$ increases with increasing $f$. Here, although the $u_f$ at 50 Hz is not shown in Fig. 9, it has been confirmed that the fluctuation amplitude at 50 Hz is smaller than that at 40 Hz because the fluctuation amplitude of $x_f$ is much smaller than that at 40 Hz.

3.3 Time variations of burning velocity and unburnt gas velocity

Figure 10(a) and (b) shows the time variations of the burning velocity $S_u$ obtained from flow field measurements with PIV and of the burning velocity $S_{u(p)}$ obtained by approximating the flow field by the potential flow. For all frequencies, $S_u$ and $S_{u(p)}$ change sinusoidally, and fluctuation amplitudes of $S_u$ and $S_{u(p)}$ increase with increasing $f$. At the same $f$, the fluctuation amplitude of $S_u$ is smaller than that of $S_{u(p)}$. From the results for the static flame shown in Fig. 6, as the variation width of $S_u$ with changing $\phi$ is smaller than that of $S_{u(p)}$, it is considered that the fluctuation amplitude of $S_u$ for the dynamic flame also becomes smaller than that of $S_{u(p)}$. From Fig. 7 and Fig. 10, it is found that $S_u$ and $S_{u(p)}$ reaches maximum and minimum before the flame reaches the most upstream part and the most downstream part with increasing $f$. That is, these results suggest that there is a phase difference between the burning velocity and flame position, and the phase difference increases with increasing $f$. 

![Fig. 10 Time variations of the burning velocities $S_u$ obtained by PIV measurement (top), and $S_{u(p)}$ obtained by approximating the flow field by the potential flow (bottom) at various frequencies.](image1)

![Fig. 11 Time variations of the unburnt gas velocities $u_g$ obtained by PIV measurement (top), and $u_{g(p)}$ obtained by approximating the flow field by the potential flow (bottom) at various frequencies.](image2)

Fig. 12 Frequency characteristics of the oscillation amplitude ratio of burning velocity $\Delta S = \Delta S_d / \Delta S_s$ and $\Delta S_{(p)} = \Delta S_{d(p)} / \Delta S_{s(p)}$. $\Delta S_d$ and $\Delta S_s$ are amplitudes of burning velocity of the dynamic and static flames, respectively. The subscript (p) means the value obtained by approximating the flow field by the potential flow.

Fig. 13 Frequency characteristics of the phase differences $\alpha$ and $\beta$. $\alpha$ is phase difference when $u_f$ and $u_g$ become maximum, and $\beta$ is the difference when $u_f$ and $u_g$ become minimum. Subscript (p) means the results obtained by approximating the flow field by the potential flow.

Fig. 14 Frequency characteristics of the oscillation amplitude of unburnt gas velocity $\Delta u_g$. Subscript (p) means the results obtained by approximating the flow field by the potential flow.

3.4 Frequency characteristics of the burning velocity

Figure 12 shows the frequency characteristics of the oscillation amplitude ratio of the burning velocity $\Delta S (= \Delta S_d / \Delta S_s)$. $\Delta S_d$ and $\Delta S_s$ are oscillation amplitudes of burning velocity of the dynamic and static flames, over the same equivalence ratio range. For comparison, $\Delta S_{(p)} (= \Delta S_{d(p)} / \Delta S_{s(p)})$ that obtained by approximating the flow field by the potential flow is also shown in this figure. Both oscillation amplitude ratios at 5 Hz are almost equal to unity,
and increase with increasing $f$ until, at 40 Hz, and reaches maximum. Then, both ratios decrease with respect to $f$. These results are qualitatively consistent in this frequency range, and also similar to the results of our previous researches evaluated by the approximation of the potential flow (Suenaga et al., 2003a, 2003b, 2005). But $\Delta S$ is greater than $\Delta S_{(p)}$, the difference becomes large at 40 and 50 Hz.

Discussed below is the reason why $\Delta S_{u_d}$ becomes greater than $\Delta S_{u_f}$ with the increase in $f$. The authors discussed it as follows, with a focus on mass transport characteristics on the upstream side of the flame (Suenaga et al., 2003a, 2003b, 2005, 2007, 2010; Takahashi et al., 2005, 2006).

1. When the fuel (CH$_4$) concentration at the flame front is increasing, the flame moves upstream, and the flame moves in the direction opposite to the direction of diffusion of CH$_4$. As a result, the concentration gradient at the flame front increases and the mass flux of CH$_4$ into the flame front increases.

2. When the CH$_4$ concentration at the flame front is decreasing, the flame moves downstream, and the flame moves in the same direction as the direction of diffusion of CH$_4$. As a result, the concentration gradient decreases and the mass flux of CH$_4$ decreases.

3. For these reasons, the movement of the flame caused by the concentration fluctuations of CH$_4$ causes an increase in the amplitude of fluctuation in the velocity of transport of CH$_4$ to the flame, and causes more fluctuations in the properties of the flame than expected from the fluctuations in the equivalence ratio at the burner outlet.

Since the results obtained by PIV measurements qualitatively agree with the results of our previous researches (Suenaga et al., 2003a, 2003b, 2005), it is considered that the results by PIV can also be explained as described above.

Next, we will discuss the reason why the difference between $\Delta S$ and $\Delta S_{(p)}$ at 40 and 50 Hz is greater than that in the low frequency range. Burning velocity $S_{u_d}$ is defined as $S_{u_d} = u_f + u_g$. Thus, if the phase difference between $u_f$ and $u_g$ becomes short, it is considered that the oscillation amplitude of the burning velocity for the dynamic flame $\Delta S_{u_d}$ becomes large. That is, $S_{u_d}$ increases with decreasing the phase difference $\alpha$, which is a difference of non-dimensional time when $u_f$ and $u_g$ become maximum, respectively. In contrast, $S_{u_d}$ decreases with a decrease in the phase difference $\beta$, which is the time difference when $u_f$ and $u_g$ become minimum, respectively. As a result, $\Delta S_{u_d}$ becomes large. Figure 13 shows the frequency characteristics of the phase difference $\alpha$ and $\beta$. Subscript $(p)$ means the result obtained by approximation of the potential flow. In Fig.13, $\alpha_{(p)}$ and $\beta_{(p)}$ are almost equal regardless of $f$; these values are lower than $\alpha$ and $\beta$. Since this result means that $\Delta S$ becomes smaller than $\Delta S_{(p)}$, it shows a tendency opposite to the relation between $\Delta S$ and $\Delta S_{(p)}$ shown in Fig.12. Figure 14 shows the frequency characteristics of the oscillation amplitude of unburnt gas velocity $\Delta U_{u_f}$. In this figure, it is found that the $\Delta U_{(p)}$, which is obtained by approximation of the potential flow, decreases in the frequency range greater than 40 Hz. Because $U_{(p)}$ is proportional to the flame position $x_f$, $\Delta U_{(p)}$ decreases with decreasing the oscillation amplitude ratio of the flame position $\Delta X$ as shown in Fig. 8. On the contrary, $\Delta U_{u_f}$ obtained by PIV measurement increases in the frequency range greater than 40 Hz, so the difference between $\Delta U_{u_f}$ and $\Delta U_{(p)}$ becomes large at 40 and 50 Hz. Moreover, $\alpha$ and $\beta$ decrease in the frequency range greater than 40 Hz. Therefore, it is considered that the difference between $\Delta S$ and $\Delta S_{(p)}$ becomes large at 40 and 50 Hz. In this section, it was found that the frequency characteristics of the oscillation amplitude ratio of burning velocity obtained by PIV measurement qualitatively agree with that obtained by approximating the flow field by the potential flow, while differing quantitatively. In particular, in the high frequency range where the oscillation amplitude of the flame position becomes small, the approximation by the potential flow underestimates the oscillation amplitude of the unburnt gas velocity, and produces an underestimation of the amplitude ratio of burning velocity.

4. Conclusion

An experimental study was conducted on the response of a wall stagnation flow flame to sinusoidal fluctuations in the equivalence ratio. Methane was used as the fuel and air was used as an oxidizer. The mean equivalence ratio and the amplitude of the equivalence ratio were 0.85 and 0.05, respectively. The fluctuation frequency of the equivalence ratio was varied from 5 to 50 Hz. The unburnt gas velocity was measured using PIV measurements, and the time variations of the burning velocity was determined from the unburnt gas velocity and the flame moving velocity. The burning velocity was compared with the time variations of the burning velocity obtained by approximating the flow field by a potential flow. The results obtained are summarized as follows.

1. The burning velocity obtained by the two methods reaches maximum (minimum) before the flame reaches the most upstream (the most downstream) part.
(2) The unburnt gas velocity obtained by PIV measurements reaches maximum (minimum) after the flame reaches the most upstream (the most downstream) part.

(3) The oscillation amplitude of the flame position changed quasi-steadily in the low frequency range, decreasing with increasing frequency in the frequency range greater than 40 Hz.

(4) The oscillation amplitude of the burning velocity for the dynamic flame $\Delta Su_d$ obtained by PIV measurement increases with respect to frequency, reaches maximum at 40 Hz. The maximum value became greater than that of the static flame $\Delta Su_s$ over the same equivalence ratio fluctuation range.

(5) This tendency is similar to the result obtained by approximating the flow field by the potential flow.

(6) The frequency characteristics of the oscillation amplitude ratio of the burning velocity $\Delta S(=\Delta Su_d/\Delta Su_s)$ obtained by approximating the flow filed with the potential flow.

(7) At all frequencies, however, $\Delta S$ was quantitatively greater than $\Delta S_{\rho}$, and the difference between $\Delta S$ and $\Delta S_{\rho}$ is large in the high frequency range.

(8) This is because approximation of the flow field by the potential flow underestimates an oscillation amplitude of unburnt gas velocity, and the degree of the underestimation becomes noticeable in the high frequency range.

(9) One possible cause of this phenomenon is that the mass flux of the reactant into a dynamic flame is greater or less than that into the static flame. That is, the mass flux into the dynamic flame increases when the flame moves upstream in the direction opposite to the direction of diffusion of the reactant and decreases when it moves downstream in the same direction as the direction of diffusion of the reactant.

References


