Numerical investigation of the stagnating laminar premixed methane/air flame with fuel concentration oscillation using a four-step reaction mechanism

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Abstract
Responses of stagnating laminar methane/air premixed flames under fuel concentration oscillation, i.e., equivalence ratio oscillation, were numerically investigated using a one-step overall reaction mechanism and a four-step reaction mechanism that included CO and H$_2$ formation. The flame motion was numerically investigated for three different oscillation cases namely: lean, rich and lean-rich crossover case. Methane/air mixtures with sinusoidal equivalence ratio oscillations were issued from the burner exit with uniform 1.0 m/s velocity profiles. In the steady state condition, the one-step overall reaction mechanism and the four-step reaction mechanism had nearly the same characteristics in the lean region, while in the rich region variations in characteristics such as flame location and flame displacement speed for the four-step model were much more significant than those for the one-step model. When the equivalence ratio was oscillated, the flame location oscillated. The amplitude of the flame location oscillation did not change with the equivalence ratio oscillation when the frequency of equivalence ratio oscillation was less than 8Hz, while it decreased monotonically when it exceeded 8 Hz. Here 8 Hz corresponds to a Strouhal number (St) of unity. Thus, this result indicates that the flame was in a quasi-steady state when St<1.0 while it became unstable when St>1.0. The variation in flame location and the flame displacement speed did not follow those for the steady state condition and made a limit cycles. This was due to the back support effect. The cycles were significantly inclined at higher frequencies. In the lean condition, the limit cycle was inclined similarly for both the one-step and four-step reaction mechanisms. In the rich condition, however, the limit cycle for the four-step reaction was more inclined than that for the one-step reaction. These results show that the formation of CO and H$_2$ played an important role in the rich condition.

Key words : Numerical analysis, Flame response, Fuel concentration oscillation, Stagnating laminar flame, Methane/air premixed flame

1. Introduction

Energy demand is increasing along with the increasing population of the world. The massive consumption of non-renewable resources is a particular concern. In fact, fossil fuels are used for more than 80 percent of the world’s primary energy demand. Therefore, making advancements in combustion technology is imperative. Presently, the lean premixed combustion is used in power plants and factories to decrease fuel consumption and reduce the NO$_x$ emissions, although it sometimes induces the combustion instability. It has been determined that this instability is mainly due to
velocity and fuel concentration perturbations driven by thermal acoustic fluctuations in the combustor. Flame responses to velocity perturbations have been well investigated (Fleifil, et al., 1996; Egolfopoulos and Campbell, 1996; Im and Chen, 2000; Sung and Law, 2000; Candel, 2002), although the effects of equivalence ratio perturbations have been less well investigated (Egolfopoulos and Campbell, 1996; Marzouk, et al., 2000; Pires Da Cruz, et al., 2000; Sankaran and Im, 2002; Cho and Lieuwen 2005; Galizzi and Escudie 2006; Kang and Kyritsis 2007, 2009; Birbaud, et al., 2008) – (Ju and Lieuwen, 2005). Flame propagation in a spatial perturbation of fuel concentration such as compositionally stratified flow has been investigated (Marzouk, et al., 2000; Pires, et al., 2000; Galizzi and Escudie 2006; Kang and Kyritsis 2007, 2009) and research on both spatial and/or temporal perturbations of fuel concentration (Egolfopoulos and Campbell, 1996; Lauvergne and Egolfopoulos, 2000; Sankaran and Im, 2002; Cho and Lieuwen, 2005) has been done as well. Those researches have done in the high frequency condition that the oscillation period is shorter than flame thickness, expecting change in the flame structure by the fuel concentration oscillation.

Dynamic flame responses to fuel concentration oscillation, that is, equivalence ratio oscillation of a stagnating laminar premixed flame, were investigated using a one-step overall reaction mechanism and low frequency by Rosdzimin et al. (2012). The flame response moved making a closed cycle around the flame location for the steady state case. This behavior was induced by back support effect. The back support effect is a heat transfer between the flame and the burnt gas. Therefore, the temperature gradient was important for estimating a back support effect. However, it was pointed out that the one-step overall reaction mechanism overestimate the adiabatic flame temperature and the burning velocity for rich mixtures because CO and H$_2$ formation was not included in the one-step overall reaction mechanism (Westbrook and Dryer, 1981). The four-step reaction mechanism that included CO and H$_2$ formation was proposed by Jones and Lindstedt (1988). They demonstrated that the four-step reaction mechanism involving only major species combine acceptable mathematical tractability with good agreement for flame characteristics for both lean and rich mixtures.

Our goal for this paper is to investigate the dynamic flame responses to the equivalence ratio oscillation of a stagnating laminar premixed flame. A four-step reaction model is used to discuss in both lean and rich conditions. The discussion is focused on the low frequency range of the equivalence ratio oscillation in that the oscillation period is much larger than the flame thickness and no change in the flame structure is expected. In the present study, no detailed kinetic scheme was needed and a simplified reaction mechanism was used since the objective of this work is to examine the dynamic flame response on the fuel concentration oscillation.

2. Numerical analysis

2.1 Computational domain and boundary conditions

The computational domain along with the boundary conditions and coordinate system are shown in Fig. 1 and Fig. 2. Methane was used as the fuel because methane/air flames are well characterized in experiments and numerical calculations. The analysis was conducted in an axi-symmetrical stagnation flow field.

20 30
30 20
Stagnation wall

Fig. 1 Overall view of the computational domain
Boundary conditions are as follows: Inflow (1) is the methane/air mixture. A uniform velocity profile was assumed. The velocity and temperature were set at \( v = 1.0 \text{ m/s} \) and \( T = 300 \text{ K} \). The mass fraction of methane and air was varied sinusoidally to produce the equivalence ratio variation, keeping the volume flow rate constant. The equivalence ratio variation is expressed by \( \phi(t) = \phi_m + \phi_A \sin \omega t \). For example, the methane mass fraction is expressed by \( Y_{CH_4}(t) = Y_{CH_4,m} + Y_{CH_4,A} \sin \omega t \).

Inflow (2) is \( N_2 \) flow. \( N_2 \) was used as a co-flow. The velocity and temperature were set at \( v = 1.0 \text{ m/s} \) and \( T = 300 \text{ K} \).

Inflow (3) is air flow. The velocity and temperature were set at \( v = 0.01 \text{ m/s} \) and \( T = 300 \text{ K} \). This flow was set to prevent recirculation between the burner and the external boundary.

The centerline of the burner corresponds to the axis of symmetry. The boundary conditions were \( v_r = 0 \) and \( \frac{\partial}{\partial r} = 0 \).

The stagnation wall was treated as an impermeable wall. A no-slip boundary condition was assumed for velocity and \( \frac{\partial v_i}{\partial r} = 0 \) was assumed for all species. An adiabatic condition was assumed, then \( \frac{\partial T}{\partial r} = 0 \).

Outflows (1) and (2) are boundaries where the fluid flows out. These boundaries were assumed to be \( \frac{\partial}{\partial r} = 0 \).

The ignition zone was set to ignite the mixture. The temperature was set at \( T = 2500 \text{ K} \).

### 2.2 Governing equations

The continuity equation and the momentum equations are given as the following:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial y} (\rho v_y) + \frac{\partial}{\partial r} (\rho v_r) + \frac{\rho v_r}{r} = S_m \tag{2.1}
\]

\[
\frac{\partial}{\partial t} (\rho v_y) + \frac{1}{r} \frac{\partial}{\partial y} \left( r \rho v_y v_y \right) + \frac{1}{r} \frac{\partial}{\partial r} (r v_r v_y) = -\frac{\partial p}{\partial y} + \frac{1}{r} \frac{\partial}{\partial y} \left[ r \mu \left( 2 \frac{\partial v_y}{\partial y} - \frac{2}{3} (\nabla \cdot \mathbf{v}) \right) \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \mu \left( \frac{\partial v_y}{\partial r} - \frac{\partial v_y}{\partial y} \right) \right] + F_x \tag{2.2}
\]
where $y$ is the axial coordinate, $r$ the radial coordinate, $v_r$ and $v_y$ the axial and radial velocities, $S_m$ the source term, $p$ the static pressure, $F_x$ and $F_r$ the external forces, and $\mu$ the viscosity (ANSYS FLUENT 12.0, 2009).

The energy and species conservation equations are:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\bar{v}(\rho E + p)) = \nabla \cdot \left( k \nabla T - \sum_{j} h_{ij} \bar{J}_i + (\bar{T} \cdot \bar{v}) \right) + S_h$$

(2.4)

$$E = h - \frac{p}{\rho} + \frac{v^2}{2}$$

(2.5)

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \bar{v} Y_i) = -\nabla \cdot \bar{I}_i + R_i + S_i$$

(2.6)

with Fick’s law for molecular diffusion:

$$\bar{I}_i = -D_{i,m} \nabla Y_i - D_{T,i} \frac{\nabla T}{T}$$

(2.7)

where, $\bar{I}$ is the stress tensor, $k$ the thermal conductivity, $S_h$ the heat formation of the chemical reaction, $h$ the specific enthalpy, $\bar{J}_i$ the diffusion flux of species $i$, $T$ the temperature, $R_i$ the net rate of production of species $i$ by the chemical reaction, $S_i$ the source term, $Y_i$ the mass fraction of species $i$, $D_{i,m}$ the mass diffusivity for species $i$ in the mixture, and $D_{T,i}$ the thermal diffusion coefficient (ANSYS FLUENT 12.0, 2009).

An ideal gas assumption was used and transport properties such as the viscosity and heat conductivity of the individual species were estimated based on kinetic theory. The specific heat was calculated using a piece-wise-polynomial approximation (ANSYS FLUENT 12.0, 2009), while the value of the transport properties of the mixture were calculated by the ideal gas mixing law. The thermal diffusivity and mass diffusivity of the mixture were estimated based on kinetic theory.

### 2.3 Chemical reaction mechanism

The methane/air combustion reaction mechanism is very complex, consisting of hundreds of elementary reactions with dozens of intermediate gas species (Smith, et al., 2013). Since the objective of this work was to examine the dynamic response of the flame to the equivalence ratio oscillation, the reaction model was simplified. Rosdzimin et al. (2012) investigated a stagnating laminar premixed methane/air flame with fuel concentration oscillation using a one-step overall reaction mechanism. Westbrook and Dryer (1981) mentioned that substantial amounts of CO and H$_2$ exist in the combustion product of a rich mixture, along with CO$_2$ and H$_2$O, hence numerical analysis has to be conducted to consider the CO and H$_2$. In addition, the temperature gradient was important for investigating an effect of back support in the present study. Therefore, numerical analysis was conducted using a four-step (Jones and Lindstedt, 1988; Bibrzycki and Poinsot, 2010) reaction mechanism that included CO and H$_2$. Numerical analysis using a one-step overall reaction mechanism was also conducted for comparison. The one-step overall reaction mechanism and the four-step reaction mechanism are shown below.
One-step overall reaction mechanism:

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]  \hspace{1cm} (2.8)

The Arrhenius type reaction rate model of the one-step overall reaction mechanism:

\[ \omega_{\text{CH}_4} = 5.6 \times 10^{11} \exp \left(- \frac{2.027 \times 10^8}{	ext{RT}} \right) \times [\text{CH}_4]^{0.2} [\text{O}_2]^{1.3} \]  \hspace{1cm} (2.9)

Four-step reaction mechanism:

\[ \text{CH}_4 + \frac{1}{2}\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2 \]  \hspace{1cm} (2.10)
\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \]  \hspace{1cm} (2.11)
\[ \text{H}_2 + \frac{1}{2}\text{O}_2 \leftrightarrow \text{H}_2\text{O} \]  \hspace{1cm} (2.12)
\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \]  \hspace{1cm} (2.13)

The Arrhenius type reaction rate model of the four-step reaction mechanism:

\[ \omega_{\text{CH}_4,2\text{O}_2} = 7.824 \times 10^{13} \times \exp \left(- \frac{1.2561 \times 10^8}{\text{RT}} \right) \times [\text{CH}_4]^{0.85} [\text{O}_2]^{1.25} \]  \hspace{1cm} (2.14)
\[ \omega_{\text{CH}_4,\text{H}_2\text{O}} = 3.0 \times 10^{11} \times \exp \left(- \frac{1.2561 \times 10^8}{\text{RT}} \right) \times [\text{CH}_4]^{1.0} [\text{H}_2\text{O}]^{1.0} \]  \hspace{1cm} (2.15)
\[ \omega_{\text{H}_2,2\text{O}_2} = 8.0 \times 10^{17} \times T^{-1} \times \exp \left(- \frac{1.6748 \times 10^8}{\text{RT}} \right) \times [\text{H}_2]^{0.25} [\text{O}_2]^{1.5} \]  \hspace{1cm} (2.16)
\[ \omega_{\text{H}_2\text{O}} = 8.0 \times 10^{17} \times T^{-1} \times \exp \left(- \frac{1.6748 \times 10^8}{\text{RT}} \right) \times [\text{H}_2\text{O}]^{1.0} [\text{O}_2]^{1.0} [\text{H}_2]^{-0.75} \]  \hspace{1cm} (2.17)
\[ \omega_{\text{CO},\text{H}_2\text{O}} = 2.75 \times 10^{12} \times \exp \left(- \frac{0.8374 \times 10^8}{\text{RT}} \right) \times [\text{CO}]^{1.0} [\text{H}_2\text{O}]^{1.0} \]  \hspace{1cm} (2.18)
\[ \omega_{\text{CO}_2,\text{H}_2} = 2.75 \times 10^{12} \times \exp \left(- \frac{0.8374 \times 10^8}{\text{RT}} \right) \times [\text{CO}_2]^{1.0} [\text{H}_2]^{1.0} \]  \hspace{1cm} (2.19)

Following a suggestion by Westbrook and Dryer (1981), pre-exponential factors were adjusted, comparing the flame speeds of the numerical results with experimental results. Generally, the calibration of the pre-exponential factor is performed using a value for \( \phi \) of about 1.1, at which the flame speed is at its maximum value (Westbrook and Dryer, 1981). For this study, we calibrated the pre-exponential factor for the one-step overall reaction mechanism under the condition \( \phi = 1.1 \) as well. The pre-exponential factor for the four-step reaction mechanism was calibrated by taking into account the values \( \phi = 0.7, \phi = 1.1 \) and \( \phi = 1.3 \). This is because of the difficulty in reproducing experimental flame properties at the equivalence ratio near the lean (rich) flammability limit compared to other equivalence ratios as shown in Westbrook and Dryer (1981).
2.4 Computational method

We used calculation method same as Rosdzimin et al. (2012). ANSYS FLUENT 14.5 was employed to numerically solve a set of conservation equations. All conservation equations were solved using a segregated solver with an under relaxation method. A variable sized grid with a minimum grid size of $1 \times 10^{-5} \text{ m} \times 1 \times 10^{-5} \text{ m}$ was used. The fine grid was used to elucidate the details in the region where the flame moves in response to higher temperatures and concentration gradients around the flame zone.

The isothermal flow field was first calculated. The mixture was then artificially ignited by setting the temperature in the ignition zone (shown in Fig. 1) to $T=2500 \text{ K}$. When the reaction started and the flame was formed, the artificial ignition temperature was set to off and the flame freely moved to a stable position at which the incoming unburned velocity of the flame was equal to the laminar flame speed. Subsequently, the equivalence ratio at Inflow (1) was varied sinusoidally with the time steps $1 \times 10^{-5} \text{ s}$. The frequency of the equivalence ratio variation was varied from 2 Hz to 50 Hz.

3. Results and discussion

3.1 Measurement points

In order to discuss the flame response by using numerical results, we defined variables that represent the flame characteristics, as shown in Fig. 3. The flame location ($y_f$) was defined as the location where the heat release rate reached maximum. The flame temperature ($T_f$) was measured at the location where the velocity profile became a maximum. The unburned flow conditions, that is, the unburned incoming gas velocity ($u_f$) and the equivalence ratio ($\phi_f$) of the unburned mixture, were estimated at the location where the approaching flow velocity became a minimum, which corresponds to the upstream edge of the preheat zone.

![Figure 3 Measurement points of the respective variables along the central axis ($r = 0$)](image)

3.2 Steady state case

The steady state case is discussed to validate the reaction models. The steady state flame speed and flame temperature of the one-step overall reaction, the four-step reaction, the flame speed of experiment (Vagelopoulos, et al., 1994) and the adiabatic flame temperature (Law, 2006) are shown in Fig. 4.
Results of the one-step overall reaction model qualitatively corresponded to those of the four-step reaction model in the lean mixture case, but they did not correspond to those of the four-step reaction in the rich mixture case. The flame position is similar these response. Flame position depends on the computational domain. Therefore, I used same domain experimental data of our laboratory as the experimental results. Flame location is shown in Fig. 5.

Figure 6 shows variations in [CO]/[CO₂] and [H₂]/[H₂O] for the one-step overall reaction and the four-step reaction. For the one-step overall reaction, CO and H₂ are not included in the reaction mechanism, which resulted in value of zero for [CO]/[CO₂] and [H₂]/[H₂O] in all ranges of the equivalence ratio. On the other hand, the four-step reaction predicted monotonic increases in [CO]/[CO₂] and [H₂]/[H₂O] with increasing equivalence ratios. Increases in the [CO]/[CO₂] and [H₂]/[H₂O] with increasing the equivalence ratio are in agreement with Westbrook and Dryer (1981). These results indicate that the four-step reaction mechanism produced better equivalence ratio profiles compared to the one-step overall reaction mechanism, especially under rich conditions, because the formation of CO and H₂ was taken into account. For the present study, the four-step reaction mechanism with CO and H₂ formation was used because CO and H₂ formation plays an important role in the rich mixture case. In the paper of Westbrook and Dryer (1981), they mentioned the overestimate of adiabatic flame temperature by the single-step reaction mechanism grows with increasing equivalence ratio and is directly related to the amount of CO and H₂ in the reaction products. Actually, Fig. 6 shows that CO and H₂ exist substantially in the rich mixture. If we consider only CO₂ and H₂O the total heat of reaction, that is temperature, over predicted as well as Westbrook and Dryer (1981) and it decrease when CO and H₂ formation is taken into account as shown in Fig. 4.
3.3 Unsteady state cases

First, we considered the flame responses to fuel concentration oscillations of 10 and 50Hz for the lean, rich, and

lean-rich crossover cases. For the lean case, the mean equivalence ratio and amplitude were set at $\phi_m = 0.75$ and

$\phi_A = 0.1$; for the rich case $\phi_m = 1.15$ and $\phi_A = 0.15$; for the lean-rich crossover case $\phi_m = 1.0$ and $\phi_A = 0.3$.

Figures 7-9 show the periodic variations in the equivalence ratio at the upstream edge of the preheat zone ($\phi_f$) and the

responses of the flame temperature ($T_f$). Figures 10-12 show the flame location ($y_f$) and the flame displacement speed

($S_d$).

For the present study, the flame displacement speed was calculated using the unburned gas velocity at the

upstream edge of the flame preheat zone and the time derivative of the flame location as described in Eq. (3.1). This

definition is the same as that used in an experimental study (Hirasawa, et al., 2000).

$$S_d = u_f - dy_f/dt$$  \hspace{2cm} (3.1)

where $u_f$ is the unburned gas velocity at the upstream edge of the preheat zone and $y_f$ is the location of the flame.

In Fig.7, the lean case ($\phi_m = 0.75$, $\phi_A = 0.1$), it can be seen that the amplitude of the equivalence ratio oscillation decreased with increasing frequency. These results correspond to the results of previous studies (Lauverne and Egolfopoulos, 2000; Sankaran and Im, 2002; Rosdzimin, et al., 2012). In the lean case, the flame temperature variation was followed by the variation in the equivalence ratio. When the equivalence ratio was increased, the reaction approached the stoichiometric condition. As a result, the flame temperature increased. In addition, the results of flame temperature oscillation qualitatively correspond to those of the one-step model. On the other hand, an inverse relationship was observed between the flame temperature and the equivalence ratio for the rich case ($\phi_m = 1.15$, $\phi_A = 0.15$), as shown in Fig. 8. In this case, when the equivalence ratio is increased, the reaction departed from the stoichiometric condition. As a result, the flame temperature decreased. For the lean-rich crossover case ($\phi_m = 1.0$, $\phi_A = 0.3$), it is interesting to note that double cycles of the flame temperature variation occurred for one period of the equivalence ratio variation, as shown in Fig. 9. This double cycle was due to the reactants’ variation from lean to rich and vice versa. These double cycles were also observed in the experiment by Suenaga et al. (2003). In addition, the flame temperature gradient is shown clearly in the rich case results for the four-step model. Therefore, the one-step model underestimated the back support when considering the heat transfer between the flame and the burnt gas for rich case. The back support effect is the heat transfer between the flame and the burnt gas. Considering the flame temperature in the lean case, it was found that the flame temperature increased when the equivalence ratio increased. Therefore, the flame intensified (weakened) in the lean case compared to the steady state case when the equivalence ratio decreased (increased) because the burnt gas temperature was higher (lower). On the other hand, the flame temperature increased when the equivalence ratio decreased in the rich case. Therefore, the flame intensified (weakened) in the rich case compared to the steady state case when the equivalence ratio increased (decreased) because
the burnt gas temperature was higher (lower). In addition, the flame temperature gradient for the four-step model was significantly higher compared to that of the one-step model. Therefore, the one-step reaction mechanism underestimated the back support effect when considering the heat transfer between the flame and the burnt gas in the rich case.

Figures 9 and 10 show the dynamic responses of the lean case ($\phi_m = 0.75$, $\phi_A = 0.1$) and the rich case ($\phi_m = 1.15$, $\phi_A = 0.15$). In the lean case, the flame location moved making a closed cycle around the flame location for the steady state case. In Fig. 9(a) and (b) the dynamic responses of the flame location turn in a clockwise direction, as shown by the two arrows, for all oscillation frequencies. Similarly, the flame location moved making a closed cycle around the steady state flame location in the rich case. Moreover, in Fig. 10(a) and (b) the dynamic responses of the flame location turn in an anti-clockwise direction, as shown by the two arrows for all oscillation frequencies. These behaviors can be explained by the back support as discussed by Marzouk et al. (2000). In the previous section, we discussed the variation in the flame temperature in the lean case and found that the flame temperature increased when the equivalence ratio increased. Therefore, the flame intensified (weakened) in the lean case compared to the steady state case when the equivalence ratio decreased (increased) because the back support temperature was higher (lower). On the other hand, the flame temperature increased when the equivalence ratio decreased in the rich case. Therefore, the flame intensified (weakened) in the rich case compared to the steady state case when the equivalence ratio increased (decreased) because the burnt gas temperature was higher (lower). In addition, the flame location cycle inclined from the flame location of the steady state case with increases in the equivalence ratio oscillation frequency. This behavior is confirmed for both reaction mechanisms in the lean case, but the behavior is seen only for the four-step reaction mechanism in the rich case.

Fig. 7 Variations in the equivalence ratios at the upstream edge of the preheat zone and the flame temperatures for the lean case ($\phi_m = 0.75$, $\phi_A = 0.1$)
Fig. 8 Variations in the equivalence ratios at the upstream edge of the preheat zone and the flame temperatures for the rich case ($\phi_m = 1.15$, $\phi_A = 0.15$)

Fig. 9 Variations in the equivalence ratios at the upstream edge of the preheat zone and the flame temperatures for the lean-rich crossover case ($\phi_m = 1.0$, $\phi_A = 0.3$)
The dynamic responses of the flame displacement speeds for the lean and rich cases are shown in Fig. 10 (c) and (d) Fig. 11 (c) and (d). The flame displacement responses moved making a closed cycle around steady state flame speed, similar to the flame location oscillation. In addition, the directions of the cycles in the lean and rich cases are different. These behaviors can be explained by the back support temperature phenomenon, which was similar to that for the flame displacement cycle as discussed by Marzouk et al. (2000).

The cycle of dynamic flame response inclined from the flame location of the steady state case as the equivalence ratio oscillation frequency increased, especially for the four-step reaction mechanism. This behavior shows the effect of heat transfer. Therefore, we can state that the impact of heat transfer between the flame and burnt gas was high when a flame with equivalence ratio oscillation was investigated.

The lean-rich crossover case (\(\phi_m = 1.0\), \(\phi_A = 0.3\)) of the equivalence ratio oscillation investigation is shown in Fig. 12. The dynamic responses of the flame locations and the flame displacement speeds differ from the monotonic equivalence ratio oscillations seen in the lean and rich cases. Overall, this was expected due to the non-monotonic equivalence ratio variation when the equivalence ratio crosses the stoichiometric value. As shown in Fig. 12(a) and (b) the flame location moved to make two closed cycles and intersected near the stoichiometric equivalence ratio. These two closed cycles turn in different directions. At equivalence ratios that are less than stoichiometric, the closed cycle turned in the clockwise direction. On the other hand, the closed cycle for the equivalence ratios greater than the stoichiometric ratio turned in an anti-clockwise direction. These behaviors are similar to the lean and rich cases, which are mainly due to the back support temperature.

Figures 12 (c) and (d) show the flame displacement speeds for the lean-rich crossover case. Similar to that for the flame location, the behavior of the flame displacement speed resulted in crossed cycles. These results also show that a crossed cycle did not occur for the high equivalence ratio oscillation frequency of the one-step reaction, as shown in Fig. 12 (c), (d). This suggests that the back support effect does not reasonably predict all of the phenomena that occur in the rich case.

In the crossover case, the amplitude of the flame location and the flame displacement speed significantly decreased at the higher equivalence ratio oscillation frequency, similar to the lean and the rich cases.

Fig. 10 Dynamic responses in the lean case (\(\phi_m = 0.75\), \(\phi_A = 0.1\)) at various oscillation frequencies compared with the steady state equivalence ratio along the central axis (r=0) for (a) the flame location of the four-step reaction, (b) the flame location of the one-step reaction, (c) the flame displacement speed of the four-step reaction, and (d) the flame displacement speed of the one-step reaction.
Fig. 11 Dynamic responses in the rich case ($\phi_m = 1.15$, $\phi_A = 0.15$) at various oscillation frequencies compared with the steady state equivalence ratio along the central axis ($r=0$) for (a) the flame location of the four-step reaction, (b) the flame location of the one-step reaction, (c) the flame displacement speed of the four-step reaction, and (d) the flame displacement speed of the one-step reaction.

Fig. 12 Dynamic responses in the lean-rich crossover case ($\phi_m = 1.0$, $\phi_A = 0.3$) at various oscillation frequencies compared with the steady state equivalence ratio along the central axis ($r=0$) for (a) the flame location of the four-step reaction, (b) the flame location of the one-step reaction, (c) the flame displacement speed of the four-step reaction, and (d) the flame displacement speed of the one-step reaction.
3.4 Flame dynamics

Figure 13 (a) shows the effect of the Strouhal number on the flame oscillation amplitude. In Fig. 13, the flame oscillation amplitude significantly decreases with an increase in the oscillation frequency when the Strouhal number ($St$) is larger than 1.0. Here, the Strouhal number is defined as:

$$St = 2\pi f L / U_0$$  \hspace{1cm} (3.2)

where $f$ is the oscillation frequency, $L$ is the distance from the burner exit nozzle to the stagnation plate, and $U_0$ is the incoming velocity. The oscillation frequency significantly influences the flame oscillation amplitude when the $St > 1.0$, while the flame oscillation amplitude is almost constant when $St < 1.0$.

Figure 13 (b) shows the movement of the flame location that occurred with equivalence ratio oscillation. It shows that the flame location moved making a closed cycle around the flame location of the steady state case, when $St < 1.0$. Furthermore, the cycle of flame location cycle inclined from the flame location of the steady state case when $St$ increased.

4. Conclusion

The effect of equivalence ratio oscillation on methane/air premixed flame motion was studied computationally using an axi-symmetric stagnation flow field. The flame responses to the oscillation frequencies of equivalence ratios between 2 Hz and 50 Hz for three different mixture cases (lean, rich, and lean-rich crossover) were investigated. The equivalence ratio oscillation was set sinusoidally at the exit of the burner. Two different reaction models, a one-step overall reaction mechanism and a four-step reaction mechanism, were investigated.

Analysis of the dynamic responses of the flame locations for the lean, rich, and lean-rich crossover cases revealed an interesting set of behaviors. In the results for the four-step reaction mechanism, the flame location movements created the limit cycles around the flame locations of the corresponding equivalence ratios for the steady state condition. Considering the four-step reaction mechanism, the formation of the cycles in all of the equivalence ratio oscillation cases can be explained clearly by the back support effect.

Variations in flame displacement speed were calculated. The flame displacement speed varied by making a closed cycle around the steady state flame speed, similar to the flame location oscillation behavior.

The heat transfer between flame and burnt gas had a high impact. The influence was confirmed by comparing the...
different reaction models (the one-step overall reaction mechanism and the four-step reaction mechanism). Therefore CO and H$_2$ formation played an important role in the rich mixture case.

The amplitude of the flame location oscillation did not change for the equivalence ratio oscillation frequency less than 8Hz, while it decreased rapidly when the rate exceed it. Here 8 Hz corresponds to the Strouhal number (St) of around unity. Thus, this result indicates that the flame moved in a quasi-steady state when St < 1.0, while it became unstable when St > 1.0.

Reference


Bibrycki, J. and Poinso, T., Reduced chemical kinetic mechanisms for methane combustion in O$_2$/N$_2$ and O$_2$/CO$_2$ atmosphere. Working note ECCOMET WN/CFD/10/17, CERFACS (2010).


Smith, G.P., Golden, D.M., Frenklach, M., Moriarty, N.W., Eiteneer, B., Goldenberg, M., Bowman, C.T., Hanson, R.K., Song, S., Gardiner, Jr, W.C., Lissianski, V.V. and Qin, Z., <http://www.me.berkeley.edu/gri_mech/> (accessed on 6
June, 2013).