Measurements of laminar burning velocities and flame stability analysis for dissociated methanol–air–diluent mixtures at elevated temperatures and pressures

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Abstract
The laminar burning velocities and Markstein lengths for the dissociated methanol–air–diluent mixtures were measured at different equivalence ratios, initial temperatures and pressures, diluents (N₂ and CO₂) and dilution ratios by using the spherically outward expanding flame. The influences of these parameters on the laminar burning velocity and Markstein length were analyzed. The results show that the laminar burning velocity of dissociated methanol–air mixture increases with an increase in initial temperature and decreases with an increase in initial pressure. The peak laminar burning velocity occurs at equivalence ratio of 1.8. The Markstein length decreases with an increase in initial temperature and initial pressure. Cellular flame structures are presented at early flame propagation stage with the decrease of equivalence ratio or dilution ratio. The transition positions can be observed in the curve of flame propagation speed to stretch rate, indicating the occurrence of cellular structure at flame fronts. Mixture diluents (N₂ and CO₂) will decrease the laminar burning velocities of mixtures and increase the sensitivity of flame front to flame stretch rate. Markstein length increases with an increase in dilution ratio except for very lean mixture (equivalence ratio less than 0.8). CO₂ dilution has a greater impact on laminar flame speed and flame front stability compared to N₂. It is also demonstrated that the normalized unstretched laminar burning velocity is only related to dilution ratio and is not influenced by equivalence ratio.

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1. Introduction
Increasing concern over the fossil fuel shortage and air pollution has intensified the study on alternative fuels around the world. As one attractively potential alternative fuel using in spark-ignition engine, methanol resource is abundant and acceptable in price. But, the specific shortages of methanol—low heat value and high fuel consumption, comparing to gasoline, making the difficulty in application and development of this alternative fuel [1]. In order to solve this problem, researches using the dissociated methanol (DM) as engine fuel which was conducted to realize high efficient low emission engine fuelled with methanol [2]. Through a dissociative reaction as shown in equation (1), methanol vapor is reformed into DM and then is introduced into the intake manifolds for engine operation. The fully DM is a mixture consisting of 66.7% hydrogen and 33.3% carbon monoxide, the high hydrogen fraction in the mixture leads to combustion characteristics of DM more similar to that of pure H₂ combustion [3]. As combustion features of hydrogen, like high flame...
propagation velocity and wide flammability range \[4,5\], it is easy to realize the lean burn process in the spark-ignition engine, and improves engine thermal efficiency and low emissions \[6,7\]. Meanwhile, hydrogen-enriched combustion usually produces high NO\(_x\) emission, thus the approach like exhaust gas recirculation (EGR) should be used to decrease the NO\(_x\) emission \[8\].

\[
\text{CH}_3\text{OH} \xrightarrow{\text{catalyst}} 2\text{H}_2 + \text{CO}
\]

Up to now, most work on DM was concentrated on the engine application \[9-11\] and few report were founded for the fundamental combustion characteristics of the mixture. In order to clarify the combustion characteristics of the mixture, it is necessary to investigate the fundamental characteristics like the laminar burning velocity and flame stability. These fundamental studies cannot only provide the basic data for the mixture combustion, but also be used in engine simulation and combustion analysis.

The objectives of this paper are to experimentally study the laminar burning velocities of DM–air mixtures and DM–air–nitrogen/carbon monoxide mixtures at elevated pressures and temperatures using the spherically propagating flame in a constant volume vessel. The influences of equivalence ratio, initial temperature and pressure, diluent and dilution ratio on laminar burning velocity and Markstein length are analyzed. Meanwhile, the flame front instabilities and cellular flame structure are also analyzed.

### 2. Experimental setup and procedures

In this work, a cylindrical combustion vessel and a spherically propagating flame were used to measure the laminar burning velocities of DM–air–diluent mixtures at different initial temperatures and pressures. The DM is simulated using the 66.7% hydrogen and 33.3% carbon monoxide by volume. The dry air is simulated by 21% oxygen and 79% nitrogen by volume. Diluents are N\(_2\) and CO\(_2\). The purities of hydrogen, carbon monoxide, oxygen, nitrogen and carbon dioxide are all

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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flame area, m(^2)</td>
</tr>
<tr>
<td>L(_b)</td>
<td>Markstein length of burnt gas</td>
</tr>
<tr>
<td>P(_u)</td>
<td>Initial pressure, MPa</td>
</tr>
<tr>
<td>r(_u)</td>
<td>Flame radius, mm</td>
</tr>
<tr>
<td>S(_l)</td>
<td>Unstretched flame propagation speed, m/s</td>
</tr>
<tr>
<td>S(_n)</td>
<td>Stretched flame propagation speed, m/s</td>
</tr>
<tr>
<td>t</td>
<td>Time, s</td>
</tr>
<tr>
<td>T(_u)</td>
<td>Initial temperature, K</td>
</tr>
<tr>
<td>u(_l)</td>
<td>Unstretched laminar burning velocity, m/s</td>
</tr>
<tr>
<td>u(_l)(_0)</td>
<td>Unstretched laminar burning velocity without dilution, m/s</td>
</tr>
<tr>
<td>u(_l)(_N2)</td>
<td>Unstretched laminar burning velocity with N(_2) dilution, m/s</td>
</tr>
<tr>
<td>u(_l)(_CO2)</td>
<td>Unstretched laminar burning velocity with CO(_2) dilution, m/s</td>
</tr>
<tr>
<td>u(_n)</td>
<td>Stretched laminar burning velocity, m/s</td>
</tr>
<tr>
<td>u(_{nor})</td>
<td>Stretched mass burning velocity, m/s</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Flame stretch rate, s(^{-1})</td>
</tr>
<tr>
<td>(\delta)</td>
<td>Laminar flame thickness, mm</td>
</tr>
<tr>
<td>(\rho_b)</td>
<td>Density of burned gas, kg/m(^3)</td>
</tr>
<tr>
<td>(\rho_u)</td>
<td>Density of unburned gas, kg/m(^3)</td>
</tr>
<tr>
<td>(\phi)</td>
<td>Fuel equivalence ratio</td>
</tr>
<tr>
<td>(\phi_r)</td>
<td>Dilution ratio</td>
</tr>
<tr>
<td>(\phi_{r,N2})</td>
<td>N(_2) dilution ratio</td>
</tr>
<tr>
<td>(\phi_{r,CO2})</td>
<td>CO(_2) dilution ratio</td>
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![Experimental arrangement](image-url)
99.9%. The dilution ratio is defined as the volumetric fraction of diluents (N₂/CO₂) addition in the pre-mixture.

$$\phi_d = \frac{V_{\text{diluent}}}{V_{\text{fuel}} + V_{\text{air}} + V_{\text{diluent}}}$$  \hspace{1cm} (2)$$

Fig. 1 shows the experimental arrangement. The experimental system consists of the combustion vessel, the heating system, the ignition system, the data acquisition system, and the high-speed schlieren photography system. A preheated high-pressure stainless steel cylinder combustion vessel with central electrode ignition was used (Fig. 2). The vessel diameter was 180 mm with length of 210 mm. Two sides of the vessel are mounted with the quartz windows to allow for optical access. A high-speed digital camera operating at 10,000 frames per second was used to record the flame pictures during the flame propagation. A Kistler pressure transducer was used to record the combustion pressure. The combustion vessel was wrapped by electrical heating tape to facilitate a range of initial temperature from 310 to 410 K and initial pressures are assigned from 0.1 to 0.5 MPa. The mixtures were prepared by introducing each component according to its corresponding partial pressure for the specified overall equivalence ratio. The mixtures are ignited by the centrally located electrodes. A standard capacitive discharge ignition system is used to produce the spark. Once the combustion was completed, the combustion vessel was vacuumed and flushed with dry air 3 times to avoid the influence of the residual gas on the next experiment. A time interval of 5 min was awaited to ensure the mixture motionless at the moment ignition and to avoid the influence from wall temperature.

3. Laminar burning velocity and Markstein length

For an outwardly-propagating spherical flame, the stretched flame velocity, \(S_n\), reflecting the flame propagation speed, is derived from the flame radius vs. time:

$$S_n = \frac{dr_n}{dt}$$  \hspace{1cm} (3)$$

where \(r_n\) is the radius of the flame in Schlieren photograph and \(t\) is the elapsed time from spark ignition.

A general definition of stretch at any point on the flame surface is the Lagrangian time derivative of the logarithm of the area \(A\) of any infinitesimal element of the surface:

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A} \frac{dA}{dt}$$  \hspace{1cm} (4)$$

For the outwardly-propagating spherical flame, the flame stretch rate can be simplified as,

$$\alpha = \frac{1}{A} \frac{dA}{dt} = \frac{2}{r_n} \frac{dr_n}{dt} = \frac{2}{r_n} S_n$$  \hspace{1cm} (5)$$

In respect to the early stage of flame expansion, there exists a linear relationship between the flame speeds and the flame stretch rate [12]; that is,

$$S_l - S_n = L_b \alpha$$  \hspace{1cm} (6)$$

Where \(S_l\) is the unstretched flame propagation speed, which is obtained as the intercept value of \(S_n\) at \(\alpha = 0\) in the plot of \(S_n\) against \(\alpha\). Burnt-gas Markstein length \(L_b\) is the slope of \(S_n\) vs. \(\alpha\) curve. The diffusional-thermal instability of the flame front depends upon Markstein length. Positive value of \(L_b\), which corresponds to a Lewis number larger than unity, indicating that the flame speed decreases with the increase of the stretch rate. A negative value of \(L_b\) corresponds to a Lewis number smaller than unity, indicating that the flame speed increases with the increase of flame stretch rate. Negative values of \(L_b\) are associated with more unstable flames [13–15].

The characteristics of the igniter can influence the measured value of burning velocity. Previous study showed that the flame speeds were independent of ignition energy when flame radius is greater than 6 mm [13]. The phenomenon was also observed by Lamoureux et al. [16], Liao et al. [17] and Bradley et al. [18]. Their studies gave the value approximately to 6 mm to avoid the possible effect caused by the spark ignition. When the flame radius is smaller than 25 mm, the pressure in the constant volume combustion vessel varies little and combustion process is a constant-pressure case. Considering both avoiding the effect of ignition energy and pressure rise, the flame photos during the
range of 6–25 mm are used in the analysis. In addition, the measurements were also restricted by the occurrence of the cellular structure due to the obvious increasing of flame speed by the increased flame front area [14,18,19].

In the case of little pressure variation, a simple relationship links the unstretched flame speed $S_l$ and unstretched laminar burning velocity $u_l$ is given as,

$$u_l = \frac{\rho_b S_l}{\rho_u}$$

(7)

Where $\rho_b$ and $\rho_u$ are the densities for burned gases and unburned gases.

Due to the finite flame thickness, there exist two possible definitions for the stretched laminar burning velocity depending on whether the burning velocity is defined at the unburned gas side or at the burned gas side. These two burning velocities, which are proposed by Bradley et al. [18,20], are the stretched laminar burning velocity $u_n$ and the stretched mass burning velocity $u_{nr}$, respectively. Stretched laminar burning velocity $u_n$ and the stretched mass burning velocity $u_{nr}$ are calculated by,

$$u_n = S \left[ \frac{\rho_b}{\rho_u} \right]$$

(8)

$$u_{nr} = \frac{\rho_b}{\rho_u} (u_n - S_n)$$

(9)

Where $S$ is a rectified function and it depends upon the flame radius and the density ratio [20], and accounts for the effect of the flame thickness on the mean density of the burned gases. The expression of $S$ in the study used the formula given by Bradley et al. [18],

$$S = 1 + 1.2 \left( \frac{\delta_l}{\delta_u} \right) - 0.15 \left[ \frac{\delta_l}{\delta_u} \right]^{2}$$

(10)

Here $\delta_l$ is the laminar flame thickness, given by $\delta_l = \nu/\Lambda$, in which $\nu$ is the kinetic viscosity of the unburned mixtures determined by $\nu = \lambda/(C_p\rho_u)$. Here, $\lambda$ and $C_p$ are the unburned gas thermal conductivity and specific heat, respectively.

The flame thickness results in the difference between the stretched laminar burning velocity $u_n$ and the stretched mass burning velocity $u_{nr}$. The difference between $u_n$ and $u_{nr}$ is large during the early stage of flame propagation as the flame front is relatively thick.
4. Results and discussions

4.1. Flame propagation speeds and Markstein length

Fig. 3 shows the schlieren photographs of the DM–air flames at an equivalence ratio of 1.0, initial temperature of 310 K and initial pressure of 0.1 MPa. In this case, the smooth spherically expanding flame propagates from the vessel center. At the early stage of flame development, the cooling effect of the electrodes on the flame propagation is observed and this leads to slow flame propagation along the direction of the electrodes comparing with the vertical direction. When the flame radius has developed to a certain value, there is little effect of the electrodes. To avoid the influence from the electrodes, the flame radius used in the calculation uses the radius in the vertical direction.

Fig. 4 plots the flame radius vs. the time for DM–air mixtures at different equivalence ratios. In the early stage of flame development, the effects of ignition energy and electrode cooling can be observed, and this gives the nonlinear relationship between flame radius and the time. This is more obvious in the case of lean mixture combustion where the flame propagation speed is low. A linear relationship between the flame radius and the time is presented when flame is developed.

Fig. 5(a) shows the stretched flame propagation speed vs. the flame radius at different equivalence ratios, initial temperature of 310 K and initial pressure of 0.1 MPa. In the case of \( \phi < 0.8 \), the stretched flame propagation speed decreases slightly with the increase of flame radius. At \( \phi = 0.8 \), little variation of stretched flame propagation speed vs. the flame radius is observed. In the case of \( \phi > 0.8 \), the stretched flame propagation speed increases with the increase of flame radius. This phenomenon reveals that flame stretch is an important factor of flame propagation. The stretched flame speeds show an increasing with the increase of initial temperature and a decreasing with the increase of initial pressure and dilution ratio. Fig. 5(b) shows the stretched flame propagation speed vs. the flame radius at two diluents and dilution ratios for the stoichiometric MD–air–diluent mixtures. Mixture diluents will reduce the chance for fuel–oxygen combination and decreases the temperature as diluent absorbs some of the released heat, resulting in the decrease of flame propagation speed. MD–air–CO\(_2\) mixtures give lower stretch burning velocity comparing with that of MD–air–N\(_2\) mixtures as high specific heat value of CO\(_2\) will absorb more released heat and decrease the combustion temperature.

Fig. 6 shows the stretched flame speeds vs. the flame stretch rate at different equivalence ratios, initial
temperatures, initial pressures and dilution ratios. In the early stage of the flame propagation when the flame radius is small, the stretch rate of flame front surface is large. As the flame propagates outwardly, the flame stretch rate is decreased. In the case of $\phi > 0.8$, the flame propagation speed is increased with the decrease of flame stretch rate. In the case of $\phi < 0.8$, the flame propagation speed is decreased with the decrease of flame stretch rate. At $\phi = 0.8$, little variation of flame vs. flame stretch rate is observed. Removing the data affected by ignition energy and electrodes during the early stage of flame development, a linear correlation line for the stretched flame speed and the flame stretch rate is plotted. The unstretched flame propagation speed is obtained as the intercept value of $S_n$ at $\alpha = 0$ in the plot of $S_n$ vs. $\alpha$. Importantly, this gives the value of laminar burning velocity $u_l$ from Eq. (7). In the case of $\phi > 0.8$, the gradients of the lines take the negative values, corresponding to the positive value of Markstein lengths. In contrast, in the case of $\phi < 0.8$, the gradients of the lines take the positive values, corresponding to the negative values of Markstein lengths.

In the case of DM–air–diluent mixture combustion, dilution will decrease the flame propagation speed, thus the flame stretch rate has the low value with the increase of dilution ratio at the same flame radius, and the data of $S_n$ concentrates into a narrow range of stretch rate while increasing the dilution ratio. Meanwhile, the gradients of $S_n$ vs. $\alpha$ almost take the same value regardless of the type of diluents at low dilution ratio ($\phi = 0.1$), indicating that the Markstein lengths give little variation at low dilution ratio in mixtures regardless of the diluents.

Fig. 7 gives the Markstein lengths ($L_b$) and the unstretched flame propagation speeds ($S_u$) vs. the equivalence ratios at different initial temperatures. The Markstein length increases monotonously with the increase of the equivalence ratio and decreases with the increase of initial temperature. This suggests that lean mixtures and high initial temperature will lead to the instability of the flame front. The diffusively-thermal instability of lean DM–air mixtures is stronger than that of rich mixtures, and this is consistent to the results for hydrogen combustion and high hydrogen-enriched mixture combustion [13]. The occurrence of wrinkled and cellular flame structure develops more readily at lean mixtures and high initial temperature case. The unstretched flame propagation speed increases with the increase of initial temperature due to enhanced chemical reaction rate. The peak value of the unstretched flame speed is presented at an equivalence ratio of 1.8, and this is similar to that of hydrogen-air mixture combustion.

In the case of DM–air–diluent mixture combustion, dilution will decrease the flame propagation speed, thus the flame stretch rate has the low value with the increase of dilution ratio at the same flame radius, and the data of $S_n$ concentrates into a narrow range of stretch rate while increasing the dilution ratio. Meanwhile, the gradients of $S_n$ vs. $\alpha$ almost take the same value regardless of the type of diluents at low dilution ratio ($\phi = 0.1$), indicating that the Markstein lengths give little variation at low dilution ratio in mixtures regardless of the diluents.

Fig. 7 – Markstein length and unstretched flame speed at different initial temperatures.

Fig. 8 – Markstein length and unstretched flame speed at different initial pressures.
Fig. 8 illustrates the Markstein lengths and unstretched flame propagation speeds vs. $\phi$ at different initial pressures. To eliminate the acceleration effect in the presence of the cellular structure on the flame propagation speed at high initial pressure and low equivalence ratio, the flame radius is limited to the radius before the occurrence of cellular structure. Fig. 8 shows the Markstein lengths at high equivalence ratio ($\phi \geq 2.0$). Markstein length and the unstretched flame speed decrease with the increase of initial pressure, and this indicates that the flame instability is increased with the increase of initial pressure.

Markstein lengths and unstretched flame propagation speeds vs. equivalence ratios at different dilution ratios for N$_2$ dilution and CO$_2$ dilution are demonstrated in Figs. 9 and 10 respectively. The mixture without diluent has a small variation in Markstein length with variation in equivalence ratio. This implies that mixture without diluent is less sensitive to flame stretch effects comparing to MD–air–diluent mixtures [23]. Mixture dilution will decrease the Markstein length at $\phi \leq 0.8$ and increase the Markstein length at $\phi > 0.8$. The cellular structure is suppressed by the mixture dilution. The unstretched flame propagation speed is decreased with the increase of dilution ratio. Peak value of unstretched flame speed will shift to the leaner mixture side with the increase of dilution ratio in the cases of both N$_2$ dilution and CO$_2$ dilution.

4.2. Flame stability and cellular structure

Fig. 11 shows the schlieren images of the flame at flame radius of 25 mm for different initial pressures and equivalence ratios. At the initial pressure of 0.1 MPa, smooth flame front is observed at three richer mixtures ($\phi = 1.6$, $\phi = 2.0$ and $\phi = 3.0$) and the image of lean mixture ($\phi = 0.6$) shows some cracks and
Fig. 12 – Schlieren images of flame front at flame radius of 25 mm at different equivalence ratios and N₂ dilution ratios (T₀ = 310 K, P₀ = 0.1 MPa).

Fig. 13 – Schlieren images of flame front at flame radius of 25 mm at different equivalence ratios and CO₂ dilution ratios (T₀ = 310 K, P₀ = 0.1 MPa).
cellular structure. When the initial pressure increases to 0.25 MPa, an obvious cellular structure is developed, especially for lean mixture case. When further elevating the initial pressure to 0.5 MPa, the strong cellular flame front is observed at three mixtures ($\phi = 0.6$, $\phi = 1.6$ and $\phi = 2.0$). Flame front maintains smooth surface at the richer mixture combustion ($\phi = 3.0$). This behavior is similar to hydrogen–air mixture combustion where flame stability is increased with the increase of equivalence ratio. For a specific equivalence ratio, the cellular flame structure is more easily occurred with increase of initial pressure, and this indicates the decrease of flame stability with the increase of initial pressure.

Figs. 12 and 13 show the schlieren images of laminar flame front at flame radius of 25 mm at different equivalence ratios and $N_2$ and $CO_2$ dilution ratios respectively. In cases of $\phi = 1.6$ and 2.0, the flame front keeps the smooth surface under all dilution ratios. This implies that addition of diluent into the MD–air mixtures gives little impact on the stability of the flame front at the high equivalence ratio. When the mixture becomes leaner, especially at $\phi = 0.8$ and 1.2, the cellular structure can be observed under low dilution ratios, and mixture dilution will decrease the instability of the flame and the occurrence of the cellular structure at the flame front. In the case of $\phi = 0.8$, and $CO_2$ dilution ratio of 0.4, the flame will move to the upside direction due to the body-force as flame propagation speed is largely decreased.

Fig. 14 gives the stretched flame propagation speed vs. flame radius at different equivalence ratios and diluents. In the early stage of flame propagation, the value of $S_n$ is slightly decreased and the schlieren flame photographs shows no evidence of cellularity. However, at the positions indicated by arrow-line, the flame front changes into the cellular structure and $S_n$ turns to increase continually due to the increase of the flame front area. The flame radius of this position is defined as the critical radius, $r_{cl}$. When normalized by the flame thickness, $b_i$, this radius gives the critical Peclet number, $Pe_{cl}$. Flame thickness $b_i$ is determined by $\nu/u_i$ [21]. Clearly, the value of $r_{cl}$ is increased as the equivalence ratio increases, while $r_{cl}$ is decreased with the increase of dilution ratio.

For a clear illustration of the effect of the cellular structure on the flame propagation speed, Fig. 15 plots the stretched flame speed against the stretch rate. There is a rapid increase in $S_n$ at the critical flame radius. This transition point represents the onset of the cellular structure. The critical radius corresponds to the second Peclet number, which is defined by Bradley et al. [15]. The information revealed from $S_n - \alpha$ curve is consistent with photo observation, indicating that the occurrence of flame cellular structure can also be demonstrated on $S_n - \alpha$ curve.

![Fig. 14 – Stretched flame propagation speed vs. flame radius.](image1)

![Fig. 15 – Stretched flame propagation speed vs. stretch rate.](image2)
4.3. Laminar burning velocity

Fig. 16 gives the stretched laminar burning velocity $u_{\text{l}}$ and the stretched mass burning velocity $u_{\text{mr}}$ vs. the stretch rate at different equivalence ratios, initial temperatures, initial pressures and dilution ratios respectively. The difference between the stretched laminar burning velocity and the stretched mass burning velocity can be clearly observed. The stretched laminar burning velocity, which denotes the rate of mixture entrainment, always increases as the stretch rate increases. In contrast, the mass burning velocity, which is the burning velocity related to the production of burned gases, is usually decreased as the stretch rate increases. The difference between the stretched laminar burning velocity and the stretched mass burning velocity is increased with the increase of the stretch rate and this would be due to the influence of flame thickness on burning velocities. A large value of $(u_{\text{l}} - u_{\text{mr}})$ is seen at small radius corresponding to high stretch rate, where the flame thickness is of the same order as the flame radius.

As the definition indicates, a high stretch rate corresponds to a small flame radius; thus the influence of flame thickness on the burning velocity becomes great. When the stretch rate reaches zero, the flame radius becomes infinity, thus the effect of flame thickness on burning velocity can be neglected, and $u_{\text{mr}}$ and $u_{\text{l}}$ will get the same value, $u_{\text{ul}}$, the unstretched laminar burning velocity. As shown in Fig. 16(a), the value of $(u_{\text{l}} - u_{\text{mr}})$ gives a peak value at equivalence ratio of 1.8 at the initial pressure of 0.1 MPa and the initial temperature of 310 K. This indicates that the influence of flame thickness on the burning velocity is decreased at both the rich mixture combustion and the lean mixture combustion relative to $\phi = 1.8$. As shown in Fig. 16(b), the value of $(u_{\text{l}} - u_{\text{mr}})$ is large at the initial temperature of 310 K and it decreases with the increase of initial temperature. The influence of flame thickness on the burning velocity becomes large as initial temperature decreases. As shown in Fig. 17(c), the value of $(u_{\text{l}} - u_{\text{mr}})$ gives the larger value at 0.5 MPa, and it decreases with the decrease of initial pressure. The influence of flame thickness on the burning velocity is increased as initial
pressure increases. Fig. 16(d) and (e) show that the values of $(u_n - u_{un})$ are increased with the increase of dilution ratio, and this indicates that the influence of flame thickness on the burning velocity is increased as the dilution ratio increases. As shown in Fig. 16(f), at small dilution ratio ($\phi = 0.1$), the difference $(u_n - u_{un})$ shows almost the same pattern for N$_2$ and CO$_2$ dilutions, and this implies that the influence of flame thickness on burning velocity is the same regardless of diluents at small dilution ratio.

Fig. 17 gives the unstretched laminar burning velocity $u_l$ vs. $\phi$ at different initial temperatures, initial pressures and dilution ratios. The study shows that, the burning velocity is decreased with the decrease of initial temperature and the increase of initial pressure, and it decreases with increase of dilution ratio. The suppression effectiveness of diluents on burning velocity is resulted from the increase of the specific heat of the non-fuel gases per unit oxygen concentration. The peak values of the unstretched laminar burning velocities are presented at the equivalence ratio of 1.8 for MD–air mixtures, and the position of the peak value moves slightly to the lean mixture direction with the increase of dilution ratio. The influence of mixture dilution on the laminar burning velocity...
is less at lean mixture combustion compared with the influence of mixture dilution on the laminar burning velocity at rich mixture combustion.

Fig. 18 gives the unstretched laminar burning velocity $u_l$ vs. equivalence ratio $\phi$ for CO/H$_2$ mixtures with different hydrogen fractions. For comparisons, the data of Chih-jen in literature [22] for CO–H$_2$–air flame and the data of Lamoureux et al. [16] for H$_2$–air flame are plotted in the figure. The comparison clearly shows good agreement between the present work and the previous studies. The figure shows that the measured unstretched laminar burning velocity is increased with increasing H$_2$ fraction in the CO–H$_2$–air mixtures. And the position of peak value of the unstretched laminar burning velocities moves to the lean mixture direction with the increase of H$_2$ fraction in the CO–H$_2$–air mixtures.

Fig. 19 gives the Markstein length $L_b$ vs. equivalence ratio for the CO–H$_2$–air mixtures with different hydrogen fractions. For the comparison, the data of Brown et al. [3], Prathap et al. [23] and Tang et al. [24] are also plotted in the same figure. The behavior of $L_b$ with the increase of hydrogen fraction shows the difference at different equivalence ratios. In the case of $\phi < 0.8$, $L_b$ decreases with the increase of hydrogen fraction, indicating the decrease of flame front stability as hydrogen is added. At $\phi = 0.8$, the four fuels show very similar Markstein lengths, and this reveals little influence on the flame front stability for different CO/H$_2$–air mixtures. In the case of $\phi > 0.8$, comparing to fuel with CO of 95% and H$_2$ of 5%, the addition of hydrogen leads to an increase in $L_b$, and this indicates an increase in flame front stability as hydrogen is added.

Based on the experimental data, the correlations of unstretched laminar burning velocities vs. the equivalence ratio for the MD–air–diluent mixtures is fitted to be a three-order polynomial function as form of

$$u_l = A + B\phi + C\phi^2 + D\phi^3$$

Table 1 gives the summary of the coefficients of the three-order polynomial function of unstretched laminar burning velocities vs. equivalence ratio for DM–air–diluent mixtures. The coefficients of DM–air–diluent mixtures are correlated based on the experimental data.

For a given equivalence ratio, the normalized burning velocity is plotted as a function of diluent (N$_2$ and/or CO$_2$) mole fraction and a linear relationship is presented. A line fitting is attempted for the data with and without diluent. Then the mean value of calculated $u_l/u_l^0$ at different dilution ratios is determined. The straight line obtained using these averaged values is shown in Fig. 21. The normalized burning velocities of the DM–air–N$_2$/CO$_2$ mixtures vs. the dilution ratio are correlated as following,

$$\frac{u_l}{u_l^0} = -2.60\phi N_2 + 1$$

$$\frac{u_l}{u_l^0} = -3.31\phi CO_2 + 1$$

Table 1 – Coefficients of three-order polynomial fitting curve.

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<tr>
<th>$\phi$</th>
<th>Without dilution</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
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<tr>
<td>A</td>
<td>−1.58</td>
<td>−1.44</td>
<td>−0.64</td>
<td>−0.80</td>
<td>0.91</td>
<td>−1.42</td>
<td>0.11</td>
<td>4.49</td>
<td>−3.06</td>
</tr>
<tr>
<td>B</td>
<td>4.71</td>
<td>4.27</td>
<td>1.47</td>
<td>1.19</td>
<td>−4.02</td>
<td>3.78</td>
<td>−0.98</td>
<td>−13.48</td>
<td>5.14</td>
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<td>C</td>
<td>−1.79</td>
<td>−1.84</td>
<td>0.27</td>
<td>0.60</td>
<td>5.30</td>
<td>−1.56</td>
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<td>13.20</td>
<td>−2.03</td>
</tr>
<tr>
<td>D</td>
<td>0.20</td>
<td>0.22</td>
<td>−0.37</td>
<td>−0.42</td>
<td>−1.94</td>
<td>0.19</td>
<td>−0.82</td>
<td>−4.03</td>
<td>0.0</td>
</tr>
</tbody>
</table>
where \( u^0_l = -1.58 + 4.71\phi - 1.79\phi^2 + 0.20\phi^3 \) in the range of \( \phi = 0.8-1.6 \). \( \phi_{N_2} \) and \( \phi_{CO_2} \) are mole fractions of \( N_2 \) and \( CO_2 \) dilution in the \( DM-\text{air} \)-diluent mixtures. It is clear that the right-hand side of Eqs. (12) and (13) is not equivalence ratio dependence. This linear dependence of normalized burning velocity on dilution ratio can be used for the calculation of laminar burning velocity of \( DM-\text{air} \)-diluent mixtures.

5. Conclusions

Measurements of laminar burning velocities and flame stability analysis are conducted using the outwardly spherical laminar premixed flame for \( DM-\text{air} \) mixtures. The laminar burning velocity and Markstein length at different equivalence ratios, initial temperatures, initial pressures and \( N_2/CO_2 \) dilution ratios are obtained. The main conclusions are summarized as follows.

1. Peak value of unstretched laminar burning velocity is presented at the equivalence ratio of 1.8 for \( DM-\text{air} \) mixtures. The flame propagation speed and the laminar burning velocity decreases with the increase of initial pressure and dilution ratio, and they increases with the increase of initial temperature.

2. Markstein length increases monotonously with the increase in equivalence ratio and decreases with the increase of initial temperature and initial pressure. Mixture dilution will decrease the laminar burning velocities of mixtures and increases the sensitivity of flame front to the flame stretch rate. Markstein lengths increase with the increase of dilution ratio except for very lean mixture (equivalence ratio less than 0.8). Flame front instability decreases with the increase of equivalence ratio and it increases with increase of initial pressure or initial temperature.

3. \( CO_2 \) dilution has a larger impact on the laminar flame speed and the Markstein length compared to \( N_2 \) dilution. The position of the peak values of the unstretched laminar burning velocities moves slightly to the lean mixture direction with the increase of dilution ratio.

4. On the basis of experimental data, the linear fitting lines of the unstretched laminar burning velocity vs. equivalence ratios at different \( N_2/CO_2 \) dilution ratios are correlated.

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References


