Extinction of Cylindrical Diffusion Flame*

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Abstract
An experimental study was performed on the behavior and extinction characteristics of the cylindrical diffusion flame affected by both factors of stretch and curvature. The cylindrical diffusion flame treated here has the convex curvature toward the air stream. The fuels used were propane and methane, and they were diluted with two kinds of inert gas, nitrogen and helium. The obtained results are described as follows. (1) The burner used in this study can form the cylindrical flame with good circularity. The minimum flame diameter is approximately 2.5mm. (2) The flame radius increases (decreases) with the increase in the fuel (air) flow velocity. (3) Flame luminosity has a maximum value when the air flow velocity is varied. On the other hand, the luminosity decreases monotonously with the increase in the fuel flow velocity. (4) Extinction stretch rate of counterflow propane 20%/nitrogen 80% vs. air flame is lower than that of counterflow methane 50%/nitrogen 50% vs. air flame. However, this extinction stretch rate relation is reversed in the case of cylindrical diffusion flame owing to the Lewis number effect caused by the flame curvature. (5) When the Lewis number of fuel flow is considerably larger than unity, the cylindrical diffusion flame can be formed even at the dilution rate with which the counterflow diffusion flame cannot be formed.

Key words: Diffusion Flame, Extinction, Cylindrical Flame, Flame Stretch, Curvature

1. Introduction
A turbulent flame is generally used for high-load combustors. In particular, the diffusion combustion method without self propagation is widely used because of safety considerations. The structure of a turbulent diffusion flame is regarded as an aggregation of laminar flamelets that have a curvature and are subject to stretching and contraction (1). Many studies on the effect of stretching and curvature of laminar diffusion flames have been performed (2)~(16).

Some studies have used a Tsuji Burner or counterflow nozzle burners for studies related to flames that are subject only to stretching due to a velocity gradient. These studies have investigated the effect of the diluents on the extinction characteristics and the fundamental characteristics of the structure and extinction of counterflow diffusion flames (2)~(9). Considering the unsteadiness of turbulent flames, the effect of sinusoidal velocity oscillations on counterflow diffusion flames have been investigated (7)~(9). These studies reported that when the velocity fluctuation frequency exceeds a certain level, complete extinction does not occur even though the stretch rate of unsteady flame has exceeded the extinction stretch rate of a steady flame at a certain moment. Some other studies have also been performed in which curvature was applied to counterflow diffusion flames (10),(11). One such study analyzed the structure of a convex flame when a microjet is blown into the center of a counterflow
diffusion flame (10). According to this study, in which hydrogen is used as a fuel and air as an oxidant, the flame intensity for a convex flame when a microjet is blown from the oxidant side is strengthened to a greater degree than when the microjet is blown from the fuel side; this is caused by the preferential diffusion effect. Fairly recent studies include a study regarding a cylindrical diffusion flame that stretches toward the axial direction formed by supplying the fuel (oxidant) to the surrounding area from the central axis while the oxidant (fuel) is supplied from the surrounding area toward the central axis in the cylindrical coordinate system (12)-(15). These studies, in which the fuel is diluted with inert gas, investigated the effect of the Lewis numbers of fuel flow and oxidant flow on flame condition and extinction. These experimental studies showed that the flame was wrinkled depending on the Lewis number of fuel flow, and the following phenomena were also indicated. When a hydrogen–nitrogen mixture is blown into the surrounding area from the central axis, as the stretch rate increases, the flame temperature becomes lower than the temperature of the counterflow flame because of the effect of the Lewis number caused by flame curvature. This tendency is reversed when air is blown from the central axis. In addition, it was shown that when carbon hydride is used as a fuel, the effect of the Lewis number caused by flame curvature becomes much smaller. However, the minimum diameter of flame observed in these studies is still large, about 10 mm (13)-(15). It is thought that experiments should be performed using a flame with high curvature to clearly show the effect of flame curvature on flame characteristics. Therefore, this study uses a burner that can form a cylindrical diffusion flame with higher curvature and better circularity than the flame used in previous studies. By doing so, we empirically studied the effect of flow velocities of fuel flow and oxidant flow on flame condition and extinction. The fuel was diluted with inert gas in this study; we additionally investigated the effect of inert gas on extinction.

2. Experimental setup and procedure

Figure 1 shows a schematic of the burner. The burner consists of a radial-flow nozzle burner, which was used in the previous study of a cylindrical premixed flame (16), and a stainless-steel tube 1.2 mm in diameter installed on the central axis of the nozzle burner. The outlet of the radial-flow nozzle burner is 10 mm wide and 12 mm in diameter, and the oxidant flows toward the central axis. On the side of the stainless-steel tube (i.e., the fuel tube) installed on the central axis, eight openings 0.3 mm in diameter are radially bored over the entire circumference. These openings are made on one line; 11 such lines with openings are aligned at 1-mm intervals toward the axis. Fuel flows out of these openings in the radial direction. A stagnation surface is formed between the fuel flow and the oxidant flow, and a cylindrical diffusion flame is formed in the stagnation surface neighborhood. To separate the surrounding air from the flame, nitrogen gas is supplied from both oxidant supply openings. In addition, a cooling system and an air curtain are installed upstream of the fuel supply opening to control the overheating of this fuel tube. Two kinds of gas (propane and methane) were used as fuel, while air was used as an oxidant. Nitrogen and helium were used as diluents of fuel flow. The dilution rate \( \chi_f \) is defined as \( \chi_f = \frac{Q_d}{Q_f + Q_d} \times 100[\%] \). Here \( Q_d \) and \( Q_f \) are the supply flow rates of inert gas and fuel, respectively. Table 1 shows the conditions used in this experiment: the dilution rates of the mixture of fuel and inert gas \( \chi_f \) and the Lewis number of the fuel flow \( Lef \) (i.e., the thermal diffusivity of fuel flow/the diffusion coefficient of fuel to inert gas). \( Lef \) was determined by approximating the results of references (6) and (15). In this study, considering the effect of buoyancy force, the burner was set such that the central axis faces the same direction as gravity.

The flame in each fuel flow rate and oxidant flow rate was photographed from the lower side of the burner by using a video camera (Frame rate: 60 FPS), and the flame radius
**Fig. 1** Schematic of cylindrical diffusion flame burner

### Table 1 Lewis number of fuel-diluent mixture

<table>
<thead>
<tr>
<th>Dilution rate, $\chi_f$ [%]</th>
<th>50</th>
<th>70</th>
<th>80</th>
<th>85</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_e$ of CH$_4$–N$_2$</td>
<td>1.05</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_e$ of CH$_4$–He</td>
<td></td>
<td></td>
<td>1.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_e$ of C$_3$H$_8$–N$_2$</td>
<td>1.39</td>
<td>1.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_e$ of C$_3$H$_8$–He</td>
<td></td>
<td></td>
<td>1.84</td>
<td>2.32</td>
<td></td>
</tr>
</tbody>
</table>

$r_f$ was determined by image analysis. The flame luminosity $L_f$ (256-step gradation), which can be regarded as one of the criteria used to indicate combustion intensity, was also obtained. The extinction experiment was performed as follows. Maintaining the fuel supply velocity $v_f$ constant, the flame was extinguished by gradually increasing the air flow velocity $v_a$ at the outlet of the radial-flow nozzle burner. Next, we determined air flow velocity at extinction, $v_{a,ext}$. Here, $v_f$ was obtained by dividing the flow rate of the mixture of fuel and inert gas supplied by the surface area of the 10-mm fuel tube including the fuel supply openings. The flame radius at extinction $r_{f,ext}$ was obtained by extrapolating the results of $v_a$ and $r_f$ at each $v_f$ before extinction. The stretch rate was defined as follows. The flame focused on by this study is subjected to stretching due to the velocity gradient of the flow and the flame curvature. For a radial distance $r$ from the center and a flow field approximated as a potential flow, the radial velocity $v_r$ is given as follows:

$$ v_r = -g \cdot r + \frac{m}{2\pi \rho r} $$  \hspace{1cm} (1)

Here, $m$ is the line source rate per unit length from the central axis, $g$ is the velocity gradient vertical to the flame sheet, and $\rho$ is the density. Substituting the velocity $v_r = v_f$ at the fuel tube outlet radius $r = R_i$, and the velocity $v_r = -v_a$ at the air outlet radius $r = R_o$, respectively, formula (1) can be rearranged as follows:

$$ g = \frac{(R_i \cdot v_f + R_o \cdot v_a)}{(R_o^2 - R_i^2)} $$  \hspace{1cm} (2)

Here, the total stretch rate $\varepsilon$ is affected by the stretching caused by the velocity gradient as well as that caused by curvature, which is given as follows:

$$ \varepsilon = 2 \cdot g $$  \hspace{1cm} (3)

In the range of $\chi_f$ considered in this study, it is noted that the flame is formed on the oxidant side. The extinction stretch rate $\varepsilon_{ext}$ was calculated by substituting $v_a$ and $v_f$ at extinction into formulas (2) and (3).
3. Results and discussion

3.1 Flame condition

Figure 2 shows an example of the flame observed in this study. Figure 2 (a) shows a flame where propane was used as fuel, the fuel dilution rate $\chi_f$ was 80%, the fuel flow velocity $v_f$ was 20 cm/s, and the air flow velocity $v_a$ was 10 cm/s. Figure 2 (b) is a flame where methane was used as fuel, with $\chi_f = 50\%$, $v_f = 80$ cm/s, and $v_a = 60$ cm/s. Nitrogen was used as diluent. In both images, it appears as if the top part of the flame is cut; however, this is only because the fuel tube overlaps with the flame in this region. This figure shows that the circularity of each flame is well independent of fuel type. All of the flames obtained in this experiment had a high circularity (as seen in these photos) and excellent uniformity, and no cellular flame similar to that observed in Hu et al. (13),(15) was observed. The minimum flame diameter observed in this study was about 2.5 mm, which was approximately 1/4th the minimum flame diameter observed in the previous studies (13)–(15). In the extinction experiment, the flame was not extinguished locally, but the entire flame was extinguished at once.

(a) C3H8-N2 vs. air flame  
(b) CH4-N2 vs air flame

Fig. 2 Images of cylindrical diffusion flame (Experimental conditions,  
(a): $\chi_f=80\%$, $v_f=20$[cm/s], $v_a=10$[cm/s].(b):$\chi_f=50\%$, $v_f=80$[cm/s], $v_a=60$[cm/s])

3.2 Flame radius and flame luminosity

For a flame using propane-nitrogen/air at a dilution rate of $\chi_f = 80\%$, Figure 3 (a) shows the flame radius $r_f$ and the flame luminosity $L_f$ for the air flow velocity $v_a$ when the fuel flow velocity is $v_f = 20$ cm/s and 50 cm/s. Figure 3 (b) indicates $r_f$ and $L_f$ for $v_a$ in the cases of $v_a = 30$, 50, and 80 cm/s. When comparing the effect of $v_a$ and $v_f$ on $r_f$, Figure 3 (a) shows that $r_f$ significantly decreased as $v_a$ increased at first, but the change in $r_f$ became moderate as $v_a$ increased further. In contrast, according to Figure 3 (b), although $r_f$ increased as $v_f$ increased, the change in $r_f$ for $v_f$ was small when $r_f$ for $v_a$ in the same flow velocity range was compared. When the location of the stagnation region $r_s$ in this flow velocity field was evaluated using formulas (1) and (2), the change in $r_s$ for $v_a$ was smaller than that of $r_s$ for $v_f$, which matched the result of Figure 3 quantitatively. Next, the effect of $v_a$ and $v_f$ on $L_f$ is compared. Regarding the change in $L_f$ for $v_a$ shown in Figure 3 (a), since $r_f$ decreased as $v_a$ increased, it was expected that the flame moved closer to the fuel tube and became weak due to heat loss. However, $L_f$ increased once as $v_a$ increased, which indicated that the combustion intensity was strengthened. However, when $v_a$ reached a certain level, $L_f$ appeared to be decreasing, weakening the combustion intensity. In contrast, Figure 3 (b) shows that $L_f$ decreased monotonously as $v_f$ increased.
The cause of this phenomenon is examined here by using the Lewis number $Le_i (= a/D_i$, $a$: thermal diffusion rate of the mixture; $D_i$: diffusion coefficient of reactant $i$). In general, when the effect of Lewis number on the stagnation flow flame is discussed, heat efflux and reactant influx through the stream tube wall are considered. In other words, when $Le_i > 1$, the heat efflux rate is larger than the reactant influx rate, thus the flame is weakened. When $Le_i < 1$, this phenomenon is reversed. However, where the flame takes the form of a cylindrical flame, the transport patterns of heat and reactant differ inside and outside the flame, compared to the case of a stretched flat flame. That is, heat is transferred convergently to the reactant inside the flame, whereas reactant is transferred divergently to the flame. The Lewis number of oxygen $Le_o$ in the air flow used in this study is almost 1, and that of the fuel flow $Le_f$ is greater than 1. Therefore, the effect of preheat effect becomes significant due to heat concentration on the fuel side of the flame. This preheat effect becomes significant as $r_f$ becomes smaller. Hence, the flame is strengthened because $r_f$ decreases as $v_a$ increases in a region where $v_a$ is small. However, when $v_a$ exceeds a certain value, the reactant goes through the flame sheet without completely reacting on it because of the threshold limit of reaction rate. This causes incomplete combustion (3), thus weakening combustion intensity. Since increase in $v_a$ reduces the distance between the flame sheet and the fuel tube, heat loss due to the fuel tube can also be expected. These effects appear in a region where $v_a$ is large, thus resulting in a decrease in the combustion intensity. On the other hand, increase in $v_f$ increases $r_f$ and decreases the heat loss from the fuel tube, but at the same time, the preheat effect is also reduced. Hence, it is likely that $L_f$ decreases monotonously as $v_f$ increases. In Figure 3 (a), $r_f$ is large when $v_f$ is greater; however, the difference between the two is considerably small compared to the effect of $v_f$ on $L_f$. Further investigation needs to be done to clarify the cause of this issue.

3.3 Effect of diluents on flame radius

Figure 4 (a) and (b) show the effect of $v_a$ on $r_f$ when propane and methane are used as fuel and nitrogen and helium as diluents. The fuel flow velocity $v_f$ is 30 cm/s in both cases.
These figures also present \( v_{a,ext} \). When \( v_f \) of helium-diluted flame is equal to \( v_f \) of nitrogen-diluted flame, the momentum of the fuel flow diluted with helium becomes smaller than that of the fuel flow diluted with nitrogen. For this reason, the stagnation surface diluted with helium moved closer to the fuel tube side, and \( r_f \) was also assumed to be reduced. However, the present results showed the opposite tendency; its cause is examined using the stoichiometric mixture fraction \( Z_{st} \). \( Z_{st} \) is given as follows (17).

\[
Z_{st} = \left[ 1 + \frac{Y_f \rho_f W_f v_f}{\nu_{\infty} W_f v_f} \right]^{-1}
\]

Here, \( Y, W, \) and \( \nu \) are mass fraction, molecular weight, and stoichiometric coefficient, respectively. The indexes \( f \) and \( o \) indicate fuel and oxygen, respectively, and \( \infty \) and \( -\infty \) indicate the boundary conditions. For a counterflow flat flame, the flame sheet is formed in the oxidant flow when \( Z_{st} < 0.5 \), while it is formed in the fuel flow when \( Z_{st} > 0.5 \). Formula (4) gives the \( Z_{st} \) value of the propane–nitrogen flame and the propane–helium flame with \( \chi_f = 85\% \) as 0.228 and 0.075, respectively, while the \( Z_{st} \) of methane–nitrogen flame and the methane–helium flame with \( \chi_f = 70\% \) is 0.228 and 0.070, respectively. Therefore, in each fuel, the \( Z_{st} \) of the helium-diluted flame was considerably smaller than that of the nitrogen-diluted flame. This fact is a major cause of increase in the \( r_f \) of the helium-diluted flame under the same \( v_a \). In addition, the \( v_{a,ext} \) of the helium-diluted flame is greater than that of the nitrogen-diluted flame. The effects of flame curvature and Lewis number of the fuel flow are associated with the abovementioned results. This will be discussed in the following section.

3.4 Effect of the flow velocity of fuel and oxidant on extinction

We now discuss the propane and methane flames when nitrogen was used as diluent. In Figures 5 and 6, panel (a) of both figures present the effect of \( v_a \) on \( r_{f,ext} \) and panel (b) of both figures present the effect of \( v_f \) on \( r_{f,ext} \). They also show extinction stretch rate \( \varepsilon_{ext} \) when \( \chi_f \) is changed. Figures 5 (a) and 6 (a) indicate that \( \varepsilon_{ext} \) increased as \( v_a \) increased, and \( r_{f,ext} \).
decreased. In contrast, Figures 5 (b) and 6 (b) show that $\varepsilon_{\text{ext}}$ decreased as $v_f$ increased, and $r_{f,\text{ext}}$ increased. Therefore, we can see here that it becomes more difficult to get the flame extinguished as $r_{f,\text{ext}}$ becomes smaller. Hu et al. (13) reported that in the case of the methane flame, the Lewis number of the fuel flow is $Lef \approx 1$, and the effect of Lewis number is very weak. However, even though in the case of the methane flame with $Lef$ slightly greater than 1, $\varepsilon_{\text{ext}}$ became greater as $r_{f,\text{ext}}$ became smaller. Since the flame that this study focuses on is considerably thinner and has a good degree of circularity, preheat due to heat concentration on the fuel side from the flame had a large effect.

Fig. 5  Effect of fuel and air flow velocity on extinction stretch rate and flame radius of C$_3$H$_8$-N$_2$ vs. air flame

Fig. 6  Effect of fuel and air flow velocity on extinction stretch rate and flame radius of CH$_4$-N$_2$ vs. air flame
3.5 Stretch rate and flame radius at extinction

Figure 7 indicates the stretch rate at extinction $\varepsilon_{\text{ext}}$ for $r_{f,\text{ext}}$. Figure 7 (a) shows the results where the $\chi_f$ of the propane and the methane flames diluted with nitrogen was 80% and 50%, respectively. In this case, $v_f$ varied from 20 to 60 cm/s at intervals of 10 cm/s. For the $\varepsilon_{\text{ext}}$ of the counterflow flat diffusion flame when the nitrogen-diluted fuel was used, the propane flame with $\chi_f = 80\%$ showed a value lower than that of the methane flame with $\chi_f = 50\%$ (6). However, in the case of the cylindrical diffusion flame, for the same value of $v_f$, the $\varepsilon_{\text{ext}}$ of the propane flame is higher than that of the methane flame. The $L_{ef}$ of the fuel flow of these flames is 1.39 for the propane flame with $\chi_f = 80\%$ and 1.05 for the methane flame with $\chi_f = 80\%$. When the $L_{ef}$ of the fuel flow is large even though different types of fuel are used, a strong preheat effect exists due to heat concentration on the fuel side. Hence, the result obtained for a cylindrical flame is reverse of that obtained for a counterflow flat flame. However, although the difference in $\varepsilon_{\text{ext}}$ between the two flames at $v_f = 20$ cm/s is approximately 50 s$^{-1}$, this difference becomes smaller at $v_f = 60$ cm/s and reaches approximately 30 s$^{-1}$. Therefore, increase in $r_f$ reduces the effect of heat concentration on the fuel side of the flame. As a result, the flame characteristics of the cylindrical flame get closer to those of the counterflow flat flame.

Figure 7 (b) shows the effect of diluents on the extinction characteristics for the propane fuel. The nitrogen-diluted flame varied in the range of $v_f = 20–40$ cm/s at intervals of 10 cm/s, while the helium-diluted flame varied in the range of $v_f = 20–45$ cm/s at intervals of 5 cm/s. Compared to the same $\chi_f$ of 85%, $\varepsilon_{\text{ext}}$ and $r_{f,\text{ext}}$ of the helium-diluted flame at $v_f = 20$ cm/s are 570 s$^{-1}$ and 1.5 mm, respectively. This shows that $\varepsilon_{\text{ext}}$ is 300 s$^{-1}$ greater and $r_{f,\text{ext}}$ is approximately 0.1 mm larger when compared to the nitrogen-diluted flame. However, $\varepsilon_{\text{ext}}$ and $r_{f,\text{ext}}$ of the helium-diluted flame with $v_f = 40$ cm/s are 240 s$^{-1}$ and 1.85 mm, respectively. The difference in $\varepsilon_{\text{ext}}$ from the nitrogen-diluted flame decreased by approximately 50 s$^{-1}$, while the difference in $r_{f,\text{ext}}$ increased by 0.35 mm. As described above, the effect of flame curvature on combustion intensity becomes significant with a slight variation in the region where the flame radius is a few mm. According to studies on the extinction characteristics of a counterflow flat diffusion flame, following results are obtained for different types of diluents. When diluting the propane fuel with helium, the stretch rate at extinction decreases linearly as the dilution rate increases, and the flame is not formed when $\chi_f$ exceeds 85% (6). However, in this study, we were able to confirm that the cylindrical helium-diluted flame was formed even for $\chi_f = 90\%$, for which the counterflow flat flame could not be formed. Here, $L_{ef} = 2.32$. This result shows that the combustion intensity of a cylindrical flame with high flame curvature could be strengthened more than that of a counterflow flat flame. For the helium-diluted flame, when $\varepsilon_{\text{ext}}$ at the same $v_f$ with $\chi_f = 85\%$ and 90% is compared, for $v_f = 30–40$ cm/s, $\varepsilon_{\text{ext}}$ with $\chi_f = 90\%$ is greater than that with $\chi_f = 85\%$. This shows that the combustion intensity could be reversed depending on the degree of flame curvature and the Lewis number. Finally, with regard to dependence of $\varepsilon_{\text{ext}}$ on $r_{f,\text{ext}}$, $\varepsilon_{\text{ext}}$ increased monotonously as $r_{f,\text{ext}}$ decreased; however, $\varepsilon_{\text{ext}}$ with $\chi_f = 90\%$ had the maximum value for $r_{f,\text{ext}}$. This is because the cooling effect introduced by using the fuel tube became strong in a region where $v_f$ is small (5). For the nitrogen-diluted flame with $\chi_f = 85\%$, $\varepsilon_{\text{ext}}$ increased monotonously as $r_{f,\text{ext}}$ decreased, and $\varepsilon_{\text{ext}}$ did not show a maximum value unlike that seen for the helium-diluted flame. This is because the thermal diffusion rate of the fuel flow of the nitrogen-diluted flame is smaller than that of the helium-diluted flame, and because the cooling effect of the fuel tube cannot be very effective even though $r_f$ is of the same value. Therefore, although this experiment was not performed from the standpoint of avoiding burnout of the fuel tube, in the nitrogen-diluted flame, $\varepsilon_{\text{ext}}$ is likely to show its maximum value where $r_{f,\text{ext}}$ is smaller.

As it is affected by both velocity gradient and flame curvature, the cylindrical flame under discussion here has a stretching effect that is more significant than in the case of the
counterflow flat diffusion flame. Where the flow field is approximated with a potential flow, the stretch rate of the cylindrical flame becomes twice that of the counterflow flat flame. The previous studies reported that when methane and propane are used as fuels, the effect of the Lewis number due to the flame curvature did not seem to exist to any visible extent (14). However, we were able to show that the Lewis number effect due to the flame curvature could be enhanced more than the combustion intensity of the counterflow flat flame by using a burner that can form a cylindrical flame having a better circularity and high curvature.

![Fig. 7  Relationship between flame radius and stretch rate at extinction](image)

4. Conclusion

By using a cylindrical diffusion flame burner, we investigated the effect of two flow velocities, fuel flow and air flow, on flame radius, flame luminosity, stretch rate at extinction, and flame radius at extinction. Fuel was supplied toward the surrounding area from the central axis and air was supplied in the reverse direction. Propane and methane were used as fuels, and air was used as an oxidant. The fuel was diluted using nitrogen and helium. Below findings were obtained:

1. The cylindrical diffusion flame burner used in this study can form a flame with good circularity. A thin flame approximately 2.5 mm in diameter was observed.

2. The flame radius becomes large as the fuel flow velocity increases; the flame radius decreases as the air flow velocity increases.

3. The flame luminosity takes the maximum value for the air flow velocity; however, the flame luminosity decreases monotonously against fuel flow velocity.

4. The stretch rate at extinction increases as the air flow velocity increases. In contrast, it decreases as the fuel flow velocity increases.

5. The counterflow propane flame with an 80% dilution rate, in which the fuel was diluted with nitrogen, has a stretch rate at extinction lower than that of the counterflow methane flame with a 50% dilution rate. However, in the case of the cylindrical flame, the combustion intensity is reversed because of the Lewis number effect due to the flame curvature.
(6) When the Lewis number of the fuel flow is great, a cylindrical diffusion flame can be formed even for dilution rates at which a counterflow flat diffusion flame cannot be formed.

References