Oxygen combustion of CH\(_4\)-CO\(_2\) mixture in a small-scale counterflow burner

Satoshi KADOWAKI*, Kota KOHATSU**, Kazuki UEHARA**, Toshiyuki KATSUMI**, Thwe Thwe Aung** and Masataro SUZUKI**
*Department of System Safety, Nagaoka University of Technology
**Department of Mechanical Engineering, Nagaoka University of Technology
1603-1 Kamitomioka, Nagaoka 940-2188, Japan
E-mail: kadowaki@mech.nagaokaut.ac.jp

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Abstract

Oxygen combustion of CH\(_4\)-CO\(_2\) mixture in a small-scale counterflow burner was studied. A diffusion flame was stabilized in the gap between opposed ports ejecting fuel and oxygen gases, and its thickness which depended on the gap distance between burner ports, inner diameter of burner tubes, flow rate of gases and fuel gas component was measured. The gas flow rates were varied such that the apparent equivalence ratio became constant at unity, while the gap distance was varied in the range from 1 mm to less. It was shown that the flame thickness decreased monotonically as the gap distance decreased and that the diffusion flame became thinner when the methane concentration in fuel gas became lower. Increased flame thickness was observed at large gas flow rate, and a diffusion flame was found in smaller gap distance at larger inner diameter. From these data, the relation between the flame thickness and the flame stretch rate was summarized, showing that the flame thickness decreased as the flame stretch became stronger, i.e. the thickness varied inversely with the square root of stretch rate. To elucidate the dependence of the flame thickness on the flame stretch rate, the flame thickness normalized by the average velocity of oxygen gas and the inner diameter was introduced. It was confirmed that the normalized flame thickness depended only on the flame stretch rate.

Keywords: Oxygen combustion of biogas, Small-scale counterflow burner, Micro diffusion flame, Flame thickness, Flame stretch rate

1. Introduction

For resolving global environmental issues, considerable efforts have been dedicated to the development and utilization of renewable energy. As one of renewable energy resources, biogas has received a lot of attention. Biogas, whose dominant components are methane and carbon dioxide, is obtained by fermentation of organic waste and livestock excreta through the action of anaerobic microorganisms (Zheng et al., 2014). The heating value of biogas is low compared with natural gas, so it is difficult to use biogas as alternative to conventional fuels for a power source. Improvements in combustion technology are required for the efficient use of biogas, a considerable amount of which is generated in organic waste disposal facilities and is just discarded so far.

To utilize biogas as a fuel for a power source of small-scale practical applications without emissions of nitrogen oxide, we need to know the characteristics of oxygen combustion of biogas in small-scale combustors, so-called micro combustors (Fernandez-Pello, 2002; Dunn-Rankin et al., 2005). Several researchers have studied oxygen combustion and clarified its fundamental phenomena (Maruta et al., 2007; Toffegaard et al., 2010; Sevaut et al., 2012; Kobayashi et al., 2013; Bongartz and Gholiemi, 2015; Shimokuri et al., 2015). Research works on micro flames have revealed the essence of small-scale combustion (Miesse et al., 2005; Chen et al., 2007; Ju and Maruta, 2011; Hirasawa et al., 2013; Saiki and Suzuki, 2013; Nakamura et al., 2017). On the basis of the knowledge on these oxygen and small-scale combustions, we can handle biogas-oxygen diffusion flames in a small-scale counterflow burner.
In our previous experiments on oxygen combustion of biogas and methane in a small-scale counterflow burner, the flame thickness was found to depend on the flame stretch rate (Kadowaki et al., 2015&2016). However, not yet clarified were the detailed characteristics of small-scale combustion, especially the relation between the flame thickness and the flame stretch rate. In this study, we perform experiments to measure the flame thickness and examine its dependence on parameters like the gap distance between burner ports, the inner diameter of burner tubes, the flow rate of gases, and the fuel gas composition. We then proposed a normalization for the flame thickness by the inner diameter and the average velocity of oxygen gas to obtain a converged relation between the normalized flame thickness and the flame stretch rate, which should clarify the characteristics of oxygen combustion of biogas in small scales.

2. Experimental design

The experimental apparatus is illustrated in Fig. 1. The burner consists of a pair of opposed stainless tubes of 1.59 mm in outer diameter and 0.4 mm or 0.6 mm in inner diameter φ. A diffusion flame is stabilized in the gap between burner ports, whose distance \(d\) is 1 mm or less. The fuel gas is a CH\(_4\)-CO\(_2\) mixture, which is an alternative of biogas in the current work, and the oxidant gas is O\(_2\). The concentration \(C_F\) of CH\(_4\) in the fuel gas is chosen in the range between 0.40 and 1.00, and the flow rates \(Q_F\) and \(Q_O\) of fuel and oxidant gases, respectively, are controlled such that the apparent equivalence ratio (overall equivalence ratio) becomes unity. The apparent equivalence ratio is estimated by the flow rates of fuel and oxidant gases. Specific values of these are shown in Table 1. The flow rate of the fuel gas is described as

\[
Q_F = Q_{CH4} + Q_{CO2}
\]

where \(Q_{CH4}\) and \(Q_{CO2}\) are the flow rates of methane and carbon dioxide, respectively. The gas flow rates were controlled by digital mass flow controllers (Azbil, MQV9020, MQV9200).

The image of micro counterflow diffusion flames is recorded by a digital microscope (Thanko, Dino-Lite Edge AMR LWD) without optical filter and converted into a binary image for measurements of the flame thickness \(\delta_f\) as shown in Fig. 2. The definition of flame thickness is because of the observation of crescent flame shapes under large gap distance. Although the flame thickness varies in accordance with the threshold brightness for the binarization, immutable is its substantial dependence on parameters like the gap distance, inner diameter, gas flow rate and fuel gas composition, provided that the threshold brightness is kept constant. These parameters are varied systematically, and the relation between the flame thickness and the flame stretch rate is clarified.

Fig. 1  Experimental apparatus for micro biogas-oxygen counterflow diffusion flames.
Table 1  Flow rates of fuel and oxidant gases.

<table>
<thead>
<tr>
<th>( C_F ) [-]</th>
<th>( Q_F ) [mL/min]</th>
<th>( Q_O ) [mL/min]</th>
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<tbody>
<tr>
<td>0.40</td>
<td>12.5</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>12.0</td>
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<tr>
<td></td>
<td>17.5</td>
<td>14.0</td>
</tr>
<tr>
<td>0.50</td>
<td>10.0</td>
<td>10.0</td>
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<tr>
<td></td>
<td>12.0</td>
<td>12.0</td>
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<tr>
<td></td>
<td>14.0</td>
<td>14.0</td>
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<tr>
<td>0.67</td>
<td>7.5</td>
<td>10.0</td>
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<tr>
<td></td>
<td>9.0</td>
<td>12.0</td>
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<td></td>
<td>7.0</td>
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</table>

Fig. 2  Definition of flame thickness.

\( (\phi = 0.6 \text{mm}, \ Q_O = 14 \text{mL/min}, \ C_F = 0.40 \text{ and } d = 1.0 \text{mm}) \)

3. Results and discussions

Figure 3 shows typical images of biogas-oxygen counterflow diffusion flames at \( Q_O = 14 \text{mL/min} \). From the comparison between images for \( \phi = 0.4 \text{ mm} \) and 0.6 mm in the top and the middle rows in this figure, respectively, it is seen that the flame shape is not noticeably changed by the inner diameter of tubes, while from the comparison between \( C_F = 1.00 \) and 0.40 in the middle and the bottom rows, the flame apparently reduces its thickness when \( C_F \) is decreased. The decrease in \( C_F \) causes also a change in the position of the flame to the right side, or the oxidant side, which is interpreted as a consequence of the increased flow rate of fuel. The comparison between \( d = 1.0 \text{ mm} \) and 0.3 mm in the left and right columns exhibits positive influence of the gap distance on the flame diameter, or the length of the flame in the radial direction. It is also noted that the flame has a crescent shape at \( d = 1.0 \text{ mm} \).

Figure 4 shows the flame thickness in biogas-oxygen counterflow diffusion flames, depending on the gap distance. It is clear that the flame thickness increases as the gap distance increases and this relation forms a line inclined upward right, but the position of the line changes depending on \( C_F \) and \( Q_O \); the line moves upward when \( C_F \) or \( Q_O \) increases. This trend is qualitatively the same for \( \phi = 0.4 \text{ mm} \) and 0.6 mm.
\[ \phi = 0.4 \text{mm}, \ C_F = 1.00, \ d = 1.0 \text{mm} \]

\[ \phi = 0.4 \text{mm}, \ C_F = 1.00, \ d = 0.3 \text{mm} \]

\[ \phi = 0.6 \text{mm}, \ C_F = 1.00, \ d = 1.0 \text{mm} \]

\[ \phi = 0.6 \text{mm}, \ C_F = 1.00, \ d = 0.3 \text{mm} \]

\[ \phi = 0.6 \text{mm}, \ C_F = 0.40, \ d = 1.0 \text{mm} \]

\[ \phi = 0.6 \text{mm}, \ C_F = 0.40, \ d = 0.3 \text{mm} \]

Fig. 3 Images of biogas-oxygen counterflow diffusion flames at \( Q_O = 14 \text{mL/min} \).

Fig. 4 Flame thickness in biogas-oxygen counterflow diffusion flames at \( \phi = 0.4 \) & 0.6mm, \( Q_O = 10, 12 \& 14 \text{mL/min} \) and \( C_F = 1.00 \) (circles) & 0.40 (triangles), depending on the gap distance.
Generally, the flame thickness is strongly affected by the flame stretch (Tsuji, 1982; Sung et al., 1995). The flame stretch rate $\kappa$ is defined as

$$\kappa = \frac{V_F + V_O}{d}$$

where $V_F$ and $V_O$ are the average velocities of fuel gas (CH$_4$-CO$_2$ mixture) and oxidant gas (O$_2$), respectively, at the ejection ports.

Figure 5 shows the relation between the flame thickness and the flame stretch rate in biogas-oxygen counterflow diffusion flames at $\phi = 0.4$ & 0.6 mm, $Q_O = 10, 12 & 14$ mL/min and $C_F = 1.00$ & 0.40. As the flame stretch rate becomes larger, the flame thickness decreases monotonically for constant $Q_O$ and $C_F$. These relations seem to shift upward in accordance with the increase in $Q_O$. It is also noticeable from the comparison between left and right figures for $\phi = 0.4$ mm and 0.6 mm, respectively, that the flame stretch has a strong influence on the flame thickness at large inner diameter.

For the unification of these dependences of the flame thickness on the flame stretch rate for various conditions of $\phi$, $Q_O$ and $C_F$, the normalized flame thickness is introduced here. The flame thickness is normalized by the average velocity of oxygen gas and the inner diameter of tubes as follows:

$$\frac{\delta_f}{V_O \cdot \phi}$$

Figures 6 and 7 show the relations between the normalized flame thickness and the flame stretch rate. These figures clearly demonstrate that the relation converges into a single line; the normalized flame thickness varies inversely with the square root of stretch rate. The results indicate that the present normalization is adequate for elucidating the effects of the flame stretch on the flame thickness. However, this normalization is not currently justified by theory. A mechanism is needed for explaining the dependence, presumably including the heat transfer from the micro flame to the burner.

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Fig. 5  Relation between the flame thickness and the flame stretch rate in biogas-oxygen counterflow diffusion flames at $\phi = 0.4$ & 0.6 mm, $Q_O = 10, 12$ & 14 mL/min, and $C_F = 1.00$ (circles) & 0.40 (triangles).
Fig. 6  Relation between the normalized flame thickness and the flame stretch rate in biogas-oxygen counterflow diffusion flames at $\phi = 0.4$ & 0.6mm, $Q_O = 10, 12 \& 14\text{mL/min}$ and $C_F = 1.00$ (circles) & 0.40 (triangles); the solid lines denote the inverse square root of stretch rate.

Fig. 7  Relation between the normalized flame thickness and the flame stretch rate in biogas-oxygen counterflow diffusion flames at $\phi = 0.4$ & 0.6mm, $Q_O = 10, 12 \& 14\text{mL/min}$ and $C_F = 1.00$ (circles), 0.67 (squares), 0.50 (diamonds) and 0.40 (triangles); the solid lines denote the inverse square root of stretch rate.
4. Conclusions

We have performed experiments of small-scale, oxy-fuel combustion of biogas to elucidate the characteristics of micro counterflow diffusion flames. The obtained results are as follows:

1. The flame thickness decreases monotonically as the gap distance decreases, and the diffusion flame becomes thinner when the methane concentration in fuel gas becomes lower.
2. Increased flame thickness is observed at large gas flow rate, and the diffusion flame is found in smaller gap distance at larger inner diameter.
3. The flame thickness decreases monotonically as the flame stretch rate becomes larger; the line representing this relation varies depending on the inner diameter, gas flow rate and fuel gas composition.
4. Those lines are converged into a single line by means of normalizing the flame thickness with respect to the average velocity of oxygen and the inner diameter of tubes; the normalized flame thickness varies inversely with the square root of the stretch rate.

The normalization of the flame thickness introduced in this work requires a theoretical justification. In the near future, we will conduct additional research on micro counterflow diffusion flames, taking account of the heat transfer from the micro flame to the burner. We are planning to clarify the mechanism of the dependence of flame size on the gap distance, inner diameter, gas flow rate and fuel gas component, and to propose the adequate model of micro counterflow diffusion flames.

References

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