A Study on the Structure of the Stable Inverse Diffusion Flame from the Producer Gas of Woody Biomass: Effects of Concentration of Carbon Dioxide on Partial Combustion

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An inverse diffusion flame is formed during the partial combustion of the reformed gas for tar reduction in the producer gas generated by the gasification of woody biomass. The polymerization and decomposition of tar occur simultaneously in the vicinity of this inverse diffusion flame. The combustion reaction of producer gas proceeds in the diluted phase. In order to decompose tar without it polymerizing into soot, it is necessary to understand the flame structure. Therefore, this study is aimed at understanding the flame structure of an inverse diffusion flame. In particular, in order to analyze the influence of the diluent, the effect of the concentration of carbon dioxide as an oxidizer on the flame structure and tar decomposition was investigated by observing the CH* chemiluminescence, the planar laser-induced fluorescence (LIF) of polycyclic aromatic hydrocarbons (PAHs), and the laser-induced incandescence (LII) of soot. The results showed that the peak intensities of CH* chemiluminescence, LIF signals from PAHs, and LII signals from soot are distributed in the stated order in a radial direction from the central axis. While PAHs are formed in the upstream of the flame and decrease gradually along the mainstream direction, the relative volume fraction of primary soot particles continued to increase along the mainstream direction. Further, a high carbon dioxide concentration resulted in a longer flame. At the same time, it led to a large volume fraction of soot downstream of the flame. As the concentration of carbon dioxide in the oxidizer increased, carbon yield decreased, suggesting an increase in soot formation.

Key Words

Tar reforming, Partial combustion, Inverse diffusion flame, PAHs, Soot

Original Paper
1. Introduction

Energy supply from renewable sources is necessary to reduce carbon dioxide footprint in the environment. In this context, woody biomass is regarded as a possible candidate for the realistic generation of renewable energy in Japan due to the abundant availability of forest stock. To use woody biomass effectively as a renewable energy source, the energy conversion process should be understood. As gasification is a commonly applied energy conversion procedure, it has been actively studied \(^{b-6}\). In addition, a combined system of gasification of woody biomass and gas engines has been proposed \(^7\). This is because the producer gas obtained from the gasification of woody biomass can be used as a gaseous fuel for reciprocating gas engines. However, the producer gas from woody biomass generally contains condensable tar, which can block pipes at low temperatures.

Therefore, tar disposal from the producer gas of woody biomass should be undertaken to achieve good efficiency in the combined system. There exist some systems, such as the so-called the gas reformers, for the disposal of tar by water washing, thermal decomposition by a catalyst, and partial combustion. In the partial combustion-type gas reformer, an oxidizer gas is flushed into the producer gas \(^8\). An inverse diffusion flame, which has fuel and oxidizer positions opposite to those in the ordinary diffusion flame, is formed. Tar polymerization and decomposition occur simultaneously in the vicinity of this inverse diffusion flame \(^8-13\). The polymerization of tar finally leads to soot formation through the formation of polycyclic aromatic hydrocarbons (PAHs). As it is difficult to decompose soot by oxidation in the downstream of the inverse diffusion flame (as this region is a reduction region), the formation characteristics of soot in the inverse diffusion flame should be carefully considered.

The producer gas of woody biomass is a multi-component mixture, including hydrogen, carbon monoxide, methane, steam, and carbon dioxide. Carbon dioxide works as a diluent for the combustion process when it is present in the unburned mixture and reduces flame temperature. It is well known that the growth of soot from PAHs is sensitive to the temperature of the combustion field \(^14\). The temperature of the system is attributed to the reactions occurring during the gasification process. There are three important reactions in this process.

\[
C_nH_m + (n/2)O_2 = (m/2)H_2 + nCO \quad (1)
\]

\[
CO + H_2O \rightarrow CO_2 + H_2 \quad (2)
\]

\[
C_nH_m + nCO_2 = (n + m/2)H_2 + 2nCO \quad (3)
\]

Equation (1) is called the hydrocarbon oxidation reaction; this is a combustion process and the reaction is exothermic in nature. Eqs. (2) and (3) are the water gas shift reaction and dry reforming, respectively \(^15\). From Eqs. (2) and (3), it can be understood that carbon dioxide affects the reforming reaction.

The purpose of this study was to clarify the effects of carbon dioxide concentration in the oxidizer on the structure of the inverse diffusion flame experimentally. The inverse diffusion flame was formed downscale in a practical partial combustion gas reformer. The spatial distributions of PAHs and soot in the vicinity of the laminar inverse diffusion flame were analyzed by laser-induced fluorescence (LIF) and laser-induced incandescence (LII), respectively. The reaction region was visualized by CH\(^+\) chemiluminescence. Furthermore, gas analysis was conducted after partial combustion to evaluate the effects of carbon dioxide on tar reformation in the inverse diffusion flame.

2. Experimental Setup and Methods

2.1 Experimental apparatus and conditions

**Fig. 1** (a) shows the experimental apparatus used in this study; it consists of a supplying system and combustion furnace. The combustion furnace was built to mimic the downscale combustor of a gas reformer. The combustion furnaces included three optical windows for observation and laser diagnostics. A circular flow field with a diameter of 50 mm was provided for fuel flow to the combustion furnace. The coaxial oxidizer supply nozzle was placed at the center of the fuel flow field. The outer diameter and inner diameter of the oxidizer supply nozzle were 17 mm and 11 mm, respectively. The average cross-sectional flow velocities of the oxidizer and fuel were 3.4 m/s and 0.65 m/s, respectively. These values were calculated from the volume-based supplying rates after taking the field temperature into account. Reynolds number in the oxidizer supply nozzle was 223; it was calculated from the kinematic viscosity coefficient using the supplying rate and temperature of the oxidizer nozzle exit. A stable laminar inverse diffusion flame was formed at the oxidizer nozzle exit.

The combustion furnace was also equipped with a sampling port to source gas samples for gas chromatography. The sampling port was placed downward of the residence zone. In the residence zone, four heaters were set in a row for controlling the temperature of the field. The burnt gas was analyzed using a simultaneous multi-component gas analyzing system (J-SCIENCE, GC7000). This gas analyzing system included two detectors, a thermal conductivity detector (TCD) and a flame ionization detector (FID), and could simultaneously analyze light gases and heavy components, such as aromatic hydrocarbons.
The specific composition of the model producer gas is shown in Table 1. This composition is based on the gasification of cedar in a rotary kiln at 600°C. Five mass flow controllers and two heaters were used to achieve consistency between the compositions and temperatures of the model producer gas and the producer gas from woody biomass (Fig. 1 (a)). Hydrogen, carbon monoxide, carbon dioxide, and methane were used as the light gas components in the model producer gas in this study. Toluene was used as the model tar to analyze the cracking and polymerization process of persistent tar. Steam was formed using a vaporizer. The flow rates of steam and toluene in the liquid phase were controlled using a dual pump; the pump was placed before the vaporizer. To quantify the flow rate of each gas species, a very small amount of argon was added to the model producer gas as reference gas.

The composition of the oxidizer are shown in Table 2. Oxygen concentration in the oxidizer was 30 vol%, which was the base condition. The chosen volume flow rate of the oxidizer, 7.75 LN/min, which resulted in an air ratio of 0.2 for the model producer gas. Four cases with varying volume concentrations of carbon dioxide were chosen.

### Table 1 Volume flow rate and mole fraction of each species in the model producer gas

| Species | Mole fraction [mol/mol] | Volume flow rate [LN/min] |
|---------|-------------------------|---------------------------|
| H₂      | 0.088                   | 2.09                      |
| CH₄     | 0.132                   | 3.14                      |
| CO      | 0.220                   | 5.24                      |
| CO₂     | 0.110                   | 2.62                      |
| C₇H₈    | 0.009                   | 0.18                      |
| H₂O     | 0.399                   | 8.86                      |
| Ar      | 0.042                   | 1                         |

### Table 2 Composition of the oxidizer in different cases

| vol% | Case1 | Case2 | Case3 | Case4 |
|------|-------|-------|-------|-------|
| O₂   | 30    | 30    | 30    | 30    |
| N₂   | 70    | 60    | 40    | 20    |
| CO₂  | 0     | 10    | 30    | 50    |

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#### 2.2 Simultaneous measurement of LII & LIF

Fig. 1 (b) shows a schematic illustration of the simultaneous LII & PAHs-LIF measurement system. The timing chart of the laser measurement system is shown in Fig. 2. Aizawa et al. reported that a broad emission with a gentle peak at 430 nm was observed in the fluorescence spectra of PAHs with 3 to 6 aromatic rings when excited by the third harmonic of a Nd:YAG laser. Bejaoui et al. also reported that transitions around 355 nm for large PAHs are characterized by small absorption cross-sections. Moderately sized PAHs (3 or 4 aromatic rings) can be
excited more efficiently than larger PAHs leading to a fluorescence signal around 450 nm \(^2\). As mentioned in the introduction section, PAHs are precursors of soot \(^2\) \(^6\) \(^\text{a}\). In our study, a Nd:YAG laser was employed as the laser source and its third harmonic was used. The repetition rate of the Nd:YAG laser was 10 Hz. The laser sheet was formed using three cylindrical lenses \((f = 40, 244, \text{and } 1020 \text{ mm})\) with an antireflection coating for light of wavelength 355 nm. The gate widths of the ICCD camera were set to 30 ns for LII and 25 ns for PAHs-LIF. The Q switch delay of the Nd:YAG laser was set to 161 \(\mu\text{s}\) based on the internal oscillation frequency of the pulse generator \((10 \text{ Hz})\). Another pulse generator confirmed the delay between the two ICCD cameras \((\text{Andor, i-Star, DH334T-25F-03})\) and the exact synchronization timing. In order to exclude light from the flame during laser diagnostics, band pass filters \((\text{PAHs-LIF, center wavelength } 498 \text{ nm, full width at half maximum (FWHМ) } 22 \text{ nm, LII, center wavelength } 400 \text{ nm, FWHМ } 60 \text{ nm})\) were attached to each camera lens. When conducting LII and LIF analyses in a field where soot and PAHs coexist, it is necessary to separate the LII signal from soot and the LIF signal from PAHs. Therefore, in this study, the LII and LIF signals were separated with an interval of 70 ns for optimizing the delay time from laser irradiation to the signal acquisition start. With the exit center of the oxidizer supply nozzle set as the origin, the \(r\)-axis was assumed to be in the radial direction and the \(z\)-axis was vertically upward; the measurement range in the radius direction was \(0 \text{ mm} \leq r \leq 19 \text{ mm}\). The laser sheet was irradiated at three positions where the center height of the laser sheet was \(z = 35, 80,\) and 140 mm. Laser power at these three positions was similar. The LII and PAHs-LIF signal intensities were integrated using 500 images. No correction of the laser sheet profile was performed.

2.3 CH* chemiluminescence measurement

CH* chemiluminescence refers to the emission from the \((0,0)\) band when the CH radical in the excited state generated by the elementary reaction \((\text{Eq. (4)})\) undergoes the transition \(A^\Delta X^\Pi\) near 430 nm \(^2\) \(^3\) \(^\text{b}\). The intensity of CH* chemiluminescence is proportional to the heat generation rate and can be used as an index of the rate of heat release during combustion \(^2\) \(^3\) \(^\text{b}\). CH* chemiluminescence was photographed using an ICCD camera \((\text{Andor, i-Star, DH334T-25F-03})\) fitted with a Nikon lens \((\text{Nikkor } 50 \text{ mm } f/1.2S)\). As the wavelength of CH* chemiluminescence was around 430 nm, an optical bandpass interference filter \((\text{center wavelength } 430 \text{ nm, FWHМ } 10 \text{ nm})\) was mounted on the lens. The exposure time of the ICCD camera was set at 5 ms. A total of 500 images were integrated to obtain an ensemble averaged image. The measurement range in the radius direction was \(0 \text{ mm} \leq r \leq 19 \text{ mm}\) and \(0 \text{ mm} \leq z \leq 180 \text{ mm}\) in the axial direction \((z\)-axis\). Because the emission intensity obtained from the CH* chemiluminescence image is line-of-sight, Abel inverse conversion was performed to obtain a cross-sectional two-dimensional distribution. In this study, considering the measurement of the stable inverse diffusion flame as axisymmetric, the intensity distribution of the CH* chemiluminescence signal in the cross section including the central axis of the inverse diffusion flame was calculated based on the principle of fully symmetric Abel inverse conversion, as proposed by Matoba et al. \(^2\) \(^3\) \(^\text{c}\).

\[
\text{C}_2 + \text{OH} = \text{CH}^* + \text{CO}
\]

\[(4)\]

3. Results and Discussion

3.1 Structure of the inverse diffusion flame

The results of optical measurement in different cases are shown in Fig. 3. Direct flame photographs are shown in Fig. 3 (i) and the cross-sectional distributions of CH* chemiluminescence are shown in Fig. 3 (ii). Peak intensities and positions in the radial direction at different heights in the PAHs-LIF and LII distributions are also shown in Fig. 3 (ii). In general, the cross section of a laser sheet has a spatial profile \(^3\) \(^\text{d}\) and it should be considered when employing LII and LIF for flame analysis. In order to suppress the influence of the laser profile, the upper and lower 5 mm ranges based on the midpoint in the longitudinal direction of the laser measurement results were used as shown in Fig. 3. All the results in Fig. 3 (ii) were normalized based on the peak intensity of each signal. Peak intensities were expressed by average values of intensity at various heights. The position of the oxidizer supply nozzle is shown in the lower part of the figure. The direct photographs of the inverse diffusion flame represent the average image of 3000 high-speed photographed images; the frame rate was 1000 fps and the exposure time was 500 \(\mu\text{s}\).

From the direct photographs, it was found that the inverse diffusion flame consisted of stable attached flames. The peak intensity of CH* chemiluminescence, LIF signals from PAHs, and LII signals from soot were distributed \((\text{in this order})\) in a radial direction from the central axis.

Near the nozzle rim in the nozzle central axis direction, the signal of CH* chemiluminescence was relatively strong. Mizutani and Yano analyzed the flame holding mechanism from the burner rim of a coaxial jet diffusion flame; the circulating flow formed downstream of the burner rim stabilizes the diffusion flame by affecting combustion near the nozzle rim \(^2\) \(^\text{e}\). In this study, the thickness of the burner rim was 3 mm and there was a velocity gradient between the fuel and oxidizer. They
provide conditions for the formation of a recirculation zone in the wake of the burner rim, which in turn promotes mixing of the fuel and oxidizer resulting in combustion. Therefore, CH⁺ chemiluminescence exhibits a relatively strong signal and it helps in flame holding and attached flames are formed.

From Fig. 3 (ii) in each case, the signal of PAHs-LIF was strong on the upstream side of the flame to the middle of the flame (around z = 80 mm). On the downstream side of the flame, the PAHs-LIF signal intensity reduced. On the upstream side of the flame, the LII signal intensity was very weak. In the middle and downstream of the flame, the LII signal intensity was very strong. PAHs-LIF can provide relative concentration measurements of PAHs within the flames 25) 26) and the LII signals are proportional to the volume fraction of the primary soot particles 27) 28). Thus, the above-described results indicate that a large amount of PAHs is formed in the upstream to the middle of the flame but only a low amount can be found at the end of the flame. On the other hand, the volume fraction of primary soot particles became high from the middle of the flame. This signal intensity increased with an increase in the distance from the burner. This result indicates that the growth of soot occurred along the fuel mainstream.

3.2 Effect of carbon dioxide concentration on CH⁺ chemiluminescence

The peak intensities of CH⁺ chemiluminescence distribution in the axial direction (z-axis) under different conditions are compared in Fig. 4. In order to make it easy to observe chemiluminescence intensity distribution, approximate curves in the height direction corresponding to CH⁺ peak intensity distribution were plotted as shown in Fig. 4. For a better fitting of the approximation curves, ninth-order approximation curves were created based on the weighted least-squares method. In the result of the CH⁺ intensity distribution in Case1 (Fig. 4), it can be seen that the peak intensity increased sharply from 0 mm to 9 mm (region 1), after which it gradually decreased from 9 mm to 131 mm (region 2), rapidly decreased from 131 mm (region 3), and finally the signal disappeared at 149 mm. Meanwhile, Case2 and Case3 have larger peak intensities in region 1. With respect to the peak intensity of CH⁺ chemiluminescence in region 2, it was found that when the concentration of carbon dioxide in the oxidizer increased, the length of region 2 increased slightly. On the other hand, the CH⁺ chemiluminescence intensity decreasing slope increases. In the case of region 3, the decreasing gradient in Case1 was larger than that in Case2. As the length of
region 2 is very large in Case3 and Case4, region 3 is not reflected in the results corresponding to Case3 and Case4. This suggests that with an increase in carbon dioxide concentration, the flame length increased.

In order to understand the effect of carbon dioxide on the flame structure, the accumulated values of CH* chemiluminescence under different conditions were compared as shown in Fig. 5. The accumulated values were obtained by calculating the sum of signals over the entire measurement range without Abel inverse conversion. This helps in evaluating the CH* chemiluminescence of the complete flame. It was found from Fig. 5 that as the concentration of carbon dioxide in the oxidizer increased, the accumulated value of the CH* signal linearly decreased. These results indicate that the concentration of carbon dioxide affects the oxidation of hydrocarbon fuels, such as methane or toluene.

3.3 Effect of carbon dioxide concentration in the oxidizer on the PAH and soot formation

The radial distribution of LII and PAHs-LIF signal intensities at z = 35, 80, and 140 mm are shown in Fig. 6. Here, z represents the height from the burner outlet. The signal intensity was normalized with the peak value. The
vertical line in the figure refers to the position of the peak intensity of CH* chemiluminescence. It can be observed in Fig. 6 that at the three positions, as the concentration of carbon dioxide in the oxidizer increases, the peak position of the LII and PAHs-LIF signals approaches the center of the nozzle. The position of the CH* peak also exhibited a similar tendency. Combined with Fig. 3, it can be concluded that the shape of the flame becomes slender with an increase in the concentration of carbon dioxide.

It can be seen in the results of PAHs-LIF (Fig. 6) that the intensity of the PAHs-LIF signal decreased with an increase in carbon dioxide concentration at z = 35 mm. At z = 35 mm, it was found that the signal intensity of Case1 remained steady, while that of Case2, 3, and 4 increased. Further, the signal intensity of Case2 exceeded the signal intensity of Case1 at z = 80 mm. Compared to the results at z = 35 mm and z = 80 mm, the signal intensity weakened under each condition at z = 140 mm.

In Fig. 6, it can be noticed that the LII intensity is weak and signal-noise ratio (S/N) is low in all cases at z = 35 mm. Comparatively, at z = 80 mm, the LII intensity increased in each case and the intensity relationship is consistent with the PAHs-LIF results at z = 80 mm. Similarly, the LII intensity in all the cases was higher at z = 140 mm when compared to the values at z = 35 and 80 mm; further, the intensity relationship of each condition is consistent with the PAHs-LIF results at z = 140 mm.

Peak intensity distribution of the PAHs-LIF and LII was normalized in the axial direction (z-axis) under each condition and compared as shown in Fig. 7 (i). The upper and lower 5 mm ranges based on the midpoint in the longitudinal direction of the laser measurement result were used in Fig. 7 (i). Bai et al. reported that the variation of carbon dioxide concentration had an effect on flame temperature. In order to consider the experimental results, the results of temperature measurement are shown in Fig. 7 (ii). It was found that the concentration of carbon dioxide had a large impact on PAH and soot formation. For case 1 (without CO2 case), however, it was out of the trend. Regarding PAHs formation, it was found that on the upstream side of the flame, the temperature of Case1 was around 1625 K, higher than other conditions. Similarly, LIF intensity of Case1 was also the strongest in all conditions. This could be explained by the fact that PAH formation was facilitated in this temperature region. With an increase in carbon dioxide concentration, on the upstream side of
the flame, PAHs formation was suppressed. In the middle part of the flame, the flame temperature of Case1 increased slightly to 1750 K, and LIF intensity remained at the same level compared with the upstream side of the flame. The temperature of Case3 (CO2-30%) rose sharply and also made the LIF intensity stronger. The temperature of Case4 (CO2-50%) was 1500 K, so LIF intensity was always the lowest. In the downstream of the flame, as the oxidation reaction proceeded, the reactants were diluted and the PAH formation reactions were gradually weakened. On the other hand, as the concentration of carbon dioxide in the oxidizer increased, the decrease in the volume fraction gradient of PAHs became smaller. It is thought that the concentration of carbon dioxide influenced the formation of PAHs and the conversion of PAHs to soot. With respect to soot formation, it was found that soot formation was weak on the upstream side and the volume fraction increased along the main flow direction in all the considered cases. In particular, the gradient with which soot volume fraction increased for z > 80 mm when the concentration of carbon dioxide in the oxidizer. On the downstream of the flame, Case1 showed a large downward trend compared to other conditions. In the inverse diffusion flame, a part of the fuel cannot react with the oxidizer because of the configuration in which the reaction region is only placed in the border of the diffusive mixing of fuel and oxidizer. Since the high temperature region is affected by the reaction region, longer flame length and longer residence time allow to have a larger high temperature region in this configuration. It is well known that the soot formation process requires high temperature and fuel rich condition at the same time. This provides a good condition for the soot formation. Therefore, Case1’s relatively short flame length should have reduced residence time, and inhibited soot growth in downstream side.

3.4 Effect of carbon dioxide concentration in the oxidizer on gas reforming

The results of gas analysis experiments in the unburnt and burnt conditions were compared. In the unburnt condition, the effect of preheating on reforming has been investigated. In the burnt condition, the effect of carbon dioxide concentration in the oxidizer on the reforming of model producer gas by partial combustion was evaluated. Fig. 8 shows the molar flow rate of carbon atoms in toluene and benzene per unit time. Fig. 9 shows the higher heating value (HHV) of hydrogen, carbon monoxide, and methane per unit time in each case. Light gases, such as ethane, ethylene, and acetylene, were also generated, but only at a rate of 0.06–0.5 kJ/min and hence were not considered in Fig. 9. The molar flow rate of carbon atoms in toluene and benzene decreased in the unburnt conditions when compared to the supply conditions. On the other hand, the HHV of hydrogen, carbon monoxide, and methane per unit time increased in the unburnt conditions as compared to the supply condition. This result implies that at 600 °C preheating, a part of toluene decomposed into light gases and benzene. Among these, the increasing of hydrogen is due to the water-gas-shift reaction (2) and steam reforming (5). The molar flow rate of carbon atoms in toluene and benzene decreased under partial combustion conditions when compared to the unburnt condition. The HHV of hydrogen, carbon monoxide, and methane per unit time reduced by about 30%–34%; in particular, methane was consumed by partial combustion. Therefore, it can be considered that methane was consumed during the combustion process and carbon monoxide and hydrogen were generated during the reforming process.

Upon comparing different cases under partial combustion conditions, it was found that the molar flow rate of carbon atoms in toluene and benzene were roughly
the same in Case1, Case2, and Case3. However, the molar flow rate of carbon atoms in toluene and benzene increased (especially in toluene) in Case4 when compared to other conditions. As the pyrolysis of toluene is temperature dependent, when the concentration of carbon dioxide in the oxidizer reached 50%, the flame temperature decreased and toluene pyrolysis was hindered. From Fig. 9, it could be inferred that as the carbon dioxide concentration in the oxidizer increased, the HHV of hydrogen, carbon monoxide, and methane per unit time decreased. This means that the decomposition of tar in the fuel gases was hindered.

\[ C_n H_m + nH_2O = (m/2)H_2 + nCO \]  \hspace{1cm} (5)

When carbon dioxide was supplied to the oxidizer, the sum of the HHV per unit time of the main light gases decreased despite the fact that the molar flow rate of the simulated tar toluene decreased. In order to examine the reason behind this observation, the influence of carbon dioxide concentration in the oxidizer on the carbon number and carbon yield in each component before and after partial combustion was investigated. **Fig. 10** shows the distribution of carbon yield of eight ingredients, including methane, carbon monoxide, carbon dioxide, ethane, ethylene, acetylene, benzene, and toluene, which could be detectable by simultaneous multi-component gas analysis. Carbon yield is defined as shown in Eq. (6). Here, \( C_{bi} \) is the amount of carbon atoms of each component in the model producer gas and \( C_s \) is the total amount of carbon atoms in the supplied gas. The undetectable part in Fig. 10 refers to the proportion of PAHs and soot that cannot be detected by the simultaneous multi-component gas analyzing system. Carbon yield in the unburnt condition was 99.92%. Therefore, it is suggested that in the preheating process, soot and PAHs did not form. Comparing different cases under partial combustion conditions, it was found that as the concentration of carbon dioxide in the oxidizer increased, carbon yield decreased and the formation of PAHs and soot increased. Here, in order to find out the source of carbon loss, various carbon components were observed. In Fig. 9, it could be observed that as the carbon dioxide concentration in the oxidizer increased, carbon monoxide decreased. On the other hand, this trend was not observed for methane, benzene, and toluene. **Fig. 11** shows the molar flow rate of carbon atoms in carbon dioxide. The molar flow rates of the supplied carbon dioxide and measured carbon dioxide in each case were compared and the amount of carbon dioxide produced or consumed in each condition was investigated. Surprisingly, as the concentration of carbon dioxide in the oxidizer increased, the carbon dioxide produced during the partial combustion process gradually decreased. In Case4, carbon dioxide was consumed.

Combined with the results described in Section 3.3, in the downstream part of the inverse diffusion flame, as the concentration of carbon dioxide in the oxidizer increased, the volume fraction of soot exhibited an increasing trend. The end portion of the flame could not be analyzed due to the limited measurement range. The gas analysis results show that soot formation downstream of the flame continued and the amount of soot and PAHs is the largest when the carbon dioxide concentration was 50%.

\[ \text{Carbon yield (\%)} = \frac{C_{bi}}{C_{s}} \times 100 \]  \hspace{1cm} (6)

**4. Conclusion**

In order to examine the inverse diffusion flame in detail, experimental studies were conducted using a downscale model of a partial combustion-type gas reformer. In particular, we investigated the structure of the inverse diffusion flame using a model of the producer gas from
the gasification of woody biomass. We also investigated the effect of carbon dioxide in the oxidizer on the partial combustion process and gas reforming. In our studies, stable inverse diffusion flames were formed and their CH\textsuperscript{*} chemiluminescence and LII and PAHs-LIF were measured. Further, a gas analysis technique was used to quantitatively evaluate the effect of the reforming process. Based on the results, the following conclusions could be drawn.

1) The peak intensities of CH\textsuperscript{*} chemiluminescence, LIF signals from PAHs, and LII signals from soot were distributed in this order in the radial direction from the central axis.

2) For a stable laminar flow inverse diffusion flame, a large amount of PAHs was formed from the upstream to the middle of flame; the PAH amount was small at the end of the flame.

3) The volume fraction of primary soot particles was high from the middle of the flame and soot growth occurred along the mainstream of the fuel.

4) The results of CH\textsuperscript{*} chemiluminescence measurement showed that the presence of carbon dioxide affected the oxidation of hydrocarbons. Specifically, a higher carbon dioxide concentration increased the flame length.

5) The concentration of carbon dioxide in the oxidizer affected the formation of PAHs and soot. Specifically, a high carbon dioxide concentration resulted in a large volume fraction of soot downstream.

6) As the concentration of carbon dioxide in the oxidizer increased, the detected carbon yield decreased and promotion of PAHs and soot was suggested.

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