Prediction of Pulverized Coal Combustibility by Measuring Chemi-luminescence of Radical Species around Tuyere

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To develop novel technologies for reducing CO₂ emission from ironmaking process, steelmaking companies in Japan are engaging in the national project called COURSE50. In this project, a large amount of H₂ is co-injected into blast furnace (BF) with pulverized coal (PC). In order to clarify how the co-injection affects PC combustibility, PC combustibility should be measured in COURSE50 BF. However, it was difficult to measure PC combustibility in BF without bothering operation. Therefore, we developed the non-contact measurement method for PC combustibility (ηPC) by utilizing chemi-luminescence spectra of PC combustion field in the lab-scale combustion furnace. We also applied the method to the COURSE50 experimental BF to ensure the accuracy of the method. And then we found that:

1) Several chemi-luminescence peaks of hydrocarbon radicals and coal ash were detected in the combustion field of PC. Among these peaks, the peak intensity ratio of OH radicals to CH radicals was most appropriate for deriving the formula for the ηPC estimation.

2) In the result of the measurement in COURSE50 experimental BF, ηPC in the experimental BF that estimated by the formula agreed well with the results in lab-scale combustion furnace. The validity of the method for estimating ηPC was confirmed.

KEY WORDS: COURSE50; ironmaking; blast furnace; CO₂; pulverized coal injection; COG; chemi-luminescence.

1. Introduction

In recent years, strong demand for the reduction of CO₂ emissions emerged in the world to control the progress of global warming. The demand also affects all companies in our country, regardless of type of business. In particular, CO₂ emissions from the steel industry account for approximately 12.7% of Japan’s total emissions, so the social responsibility of the steel industry in reducing CO₂ emissions is very significant. In response to this background, Japanese steelmaking companies are conducting various R&D projects for reducing CO₂ emissions, including COURSE50 (CO₂ Ultimate reduction system for Cool Earth 50) project. COURSE50 is the national contract research project, which all of integrated steelmaking companies in Japan participate in, and is the project for developing technology to reduce CO₂ emissions from ironmaking processes by 30%. One of the main ideas in COURSE50 is the co-injection of a large amount of hydrogen with pulverized coal (PC) into blast furnace (BF) from its tuyeres. With this idea, we can replace the direct reduction (shown in Eq. (1)) with hydrogen reduction (shown in Eq. (2)) and then decrease specific CO₂ emission from BF.

\[
C + FeO \rightarrow CO + Fe \quad \text{(1)}
\]

\[
H_2 + FeO \rightarrow H_2O + Fe \quad \text{(2)}
\]

One of the problems in co-injecting a large amount of hydrogen with PC is the change of PC combustion behavior. In these days, PC is commonly blown into BF in Japan. The general size of PC is around 100 μm or less. When hydrogen is co-injected with PC, hydrogen and PC will burn in the same combustion field. In general, gas burns faster than solid. Therefore, hydrogen burns faster than PC and consumes oxygen in advance, and it may deteriorate PC combustibility. Deterioration in PC combustibility increases unburnt char which accumulates in BF and deteriorates the permeability of liquid in deadman. Therefore, it is important to understand PC combustion behavior in co-injecting hydrogen in order to maintain stable BF operation.

PC combustion behavior in blast furnaces and experimental furnaces simulating BF have been measured by various methods in the past. In those cases, PC combustibility was mainly calculated by analyzing components of unburnt char or gas sampled from PC combustion field. However,
temperature and pressure in BF are too high to install stable equipment for sampling unburnt char or gas in operating BF. Though temporal measurement is possible, it is difficult to measure PC combustibility regularly in operating BF because it may bother stable operation.

In this study, to develop a non-contact method for measuring the PC combustibility, we focused on the spectroscopic measurement of combustion flames. It is known that reaction intermediates (radicals) exist in the combustion process of hydrocarbon and those radicals show chemiluminescence in the transition process from the excited state to the ground state.\(^{10,11}\) In the case of methane and other gaseous hydrocarbons, many reports studied the combustion behavior by analyzing changes in the type and intensity of chemiluminescence.\(^{12,13}\) On the other hand, in the case of solid hydrocarbons such as PC, combustion behavior was studied from the aspect of the chemi-luminescence of ash elements,\(^{14}\) but not from the aspect of radicals.

In this paper, we investigated relationships between PC combustion behavior and chemi-luminescence spectra of PC flame in a lab-scale furnace. From experimental results, we developed a non-contact measurement method to estimate the PC combustibility from chemi-luminescence of hydrocarbon radicals. Then, we measured spectra of PC flame in the tuyere of an experimental BF for COURSE50 (EBF), which was located in Kimitsu Area, East Nippon Works of Nippon Steel & Sumitomo Metal Corp. (currently Nippon Steel Corp.), and evaluated the validity of the measurement method for PC combustibility.

2. Development of Measurement Method for PC Combustibility with the Lab-scale Furnace

2.1. Experimental Apparatus

**Figure 1** shows a schematic diagram of the lab-scale furnace. The furnace is mainly composed of LPG burner and blowpipe. The LPG burner has two holes for inserting injection lances through which we can blow the reducing agent such as PC, CH\(_4\) and other reducing gas into the furnace. **Figure 2** shows a schematic cross-sectional diagram of the injection lance. The lance has a triple tube structure, and we can blow PC through the center pipe and reducing gas through the outside gap. We didn’t use the intermediate gap. The blowpipe has four observation windows, and three sampling holes on the opposite side of the windows. We can observe and measure combustion flame in the furnace through the windows, and we can sample gas in the furnace using a sampling sonde through the holes. As the sampling sonde, we used a stainless steel water-cooled tube which outer diameter and sampling hole diameter were respectively 35 mm and 8 mm. In the experiment, hot blast with controlled oxygen concentration was generated in the LPG burner, PC and reducing gas were blown into the hot blast from the lance, and measurement and gas sampling were carried out on the combustion field in the furnace. We carried out the measurement on the second and third window from the upstream side to ensure that the distance between the lance tip and measurement spot was the same level as the distance in EBF. We also sampled gas from 2 sampling holes on the opposite side of the windows we carried out measurements. As we had only two windows and holes for the measurement and the sampling, we carried out the experiments with changing the insertion depth of the lance to change the distance from the lance tip to each observation window. In this way, we were able to evaluate the change of the combustion behavior of the reducing agents over the distance from the lance tip.

To evaluate PC combustion behavior in the lab-scale furnace, we carried out gas sampling and analysis, measurement of chemi-luminescence spectra of combustion flame, and PC temperature in the furnace. For the measurement of chemi-luminescence spectra, we connected a spectrometer (Flame, made by Ocean Insight) to a measuring probe with a focal length of 300 mm and measured the spectra of the combustion flame from 300 to 880 nm in wavelength. For the measurement of the temperature, we used a two-color infrared thermometer (IR-FAQH, made by CHINO Corporation). For the gas sampling in the furnace, we used the sampling sonde mentioned above. The measured values of PC combustion flame showed fluctuation due to fluctuation of blast volume and PC rate. Therefore, we used the time averaged values...
as representative data in each measurement. In the chemiluminescence spectrometry, we averaged data of 25 measurements at each case and location in which we measured. In the temperature measurement, we measured temperature every 0.5 seconds for 30 seconds, and averaged the local maximum values in each measured temperature trend. The reason for averaging the local maximum is to exclude the temperature of the inner wall of the lab-scale furnace which is inevitably measured due to the discontinuity of PC flow. Similarly, we sampled gas in the furnace three times, and then averaged the gas composition at each case and location.

We calculated PC combustibility based on the mass balance of carbon atoms from the composition of sampled gas. Figure 3 shows a schematic diagram explaining the calculation method of PC combustibility. We defined the PC combustibility as the ratio of the amount of gasified carbon from PC, \( M_{C,\text{gas}} \), to the amount of carbon in PC injected into the furnace, \( M_{C,\text{PC}} \). We calculated \( M_{C,\text{PC}} \) from PC injection rate and the carbon content of PC. We calculated \( M_{C,\text{gas}} \) as follows. Firstly, we calculated the amount of gaseous carbon input, \( V_{C,\text{in}} \), from LPG and reducing gas injection rate, and carbon content of those gas species. Next, assuming that \( N_2 \) didn’t react in the furnace, we calculated the flow rates of gaseous carbon, \( V_{C,\text{gas}} \), by the concentrations of CO, CO\(_2\), CH\(_4\), and \( N_2 \) in sampled gas. We calculated \( M_{C,\text{gas}} \) from \( V_{C,\text{in}} \) and \( V_{C,\text{gas}} \). Finally, we calculated PC combustibility, \( \eta_{PC} \), by the following Eqs. (3) to (6).

\[
\eta_{PC} = \frac{M_{C,\text{gas}}}{M_{C,\text{PC}}} = \frac{V_{C,\text{gas}} - V_{C,\text{in}}}{22.4 M_{C,\text{PC}}} \quad \text{..................................(3)}
\]

\[
V_{C,\text{in}} = \sum n_{Ci} V_{i,\text{in}} \quad \text{..................................(4)}
\]

\[
V_{C,\text{gas}} = \frac{\sum \eta_{Ci} X_{i,\text{gas}}}{X_{N_2,\text{gas}}} V_{N_2,\text{in}} \quad \text{..................................(5)}
\]

\[
M_{C,\text{PC}} = \frac{X_{C,\text{PC}} m_{PC}}{12} \quad \text{..................................(6)}
\]

where \( n_{Ci} \) was the number of carbon atoms per molecule of the gas species \( i \), \( V_{i,\text{in}} \) was the flow rate of the gas species \( i \) [Nm\(^3\)/h], \( X_{i,\text{gas}} \) was the concentration of the gas species \( i \) in the sampling gas [vol%], \( X_{C,\text{PC}} \) was the mass fraction of C in PC [mass%], and \( m_{PC} \) is the injection rate of PC [kg/h].

Table 1 is a list of experimental conditions in the lab-scale furnace. In this study, the conditions were set based on the operational conditions of EBF. We carried out three cases. In Case1, we injected only PC as reducing agent. In Case2-1 and 2-2, we co-injected PC and reducing gas from the same triple-tube lance. In Case1, since chemiluminescence was not observed in the spectra of the combustion flame at the same temperature as the EBF operation (1 273 K), the experiments were conducted at higher blast temperature (1 523 K) so that we could observe chemiluminescence. We inserted the injection lance from the side of observation windows in Case1 and Case2-1, while we inserted the injection lance from the side of sampling holes in Case2-2. The direction of injection lance and that of the gas flow in the furnace were different in 20 degrees in angle, so PC could segregate into fine and coarse particles in the furnace. Coarser particles tend to segregate to the opposite side to the lance side due to its stronger inertia force than that of finer particles. Therefore, if we insert the lance from the side of observation windows, fine particles can be easily observed from the windows, and vice versa. Therefore, we conducted Case2-2 to evaluate the effect of the change of side of lance insertion on the measurement results.

Table 2 shows particle size and the result of approximate analysis of PC used in this experiment. Table 3 shows the composition of the reducing gas used in Case2-1 and 2-2. In Case2-1 and 2-2, we used simulated coke oven gas (COG) as reducing gas.

### 2.2. Experimental Results

Figure 4 shows trends of \( \eta_{PC} \) over the distance from the blast furnace.

#### Table 1. A list of experimental conditions of the lab-scale furnace.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Case1</th>
<th>Case2-1</th>
<th>Case2-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast volume [Nm(^3)/h]</td>
<td>270</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Blast temperature [K]</td>
<td>1 523</td>
<td>1 273</td>
<td>1 273</td>
</tr>
<tr>
<td>Blast ( O_2 ) [%]</td>
<td>27</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>PC injection rate [kg/h]</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Injected gas</td>
<td>( N_2 )</td>
<td>Reducing gas</td>
<td>Reducing gas</td>
</tr>
<tr>
<td>Gas injection rate [Nm(^3)/h]</td>
<td>15</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Lance insert side</td>
<td>Window side</td>
<td>Window side</td>
<td>Sampling side</td>
</tr>
</tbody>
</table>

#### Table 2. Particle size and approximate analysis of PC used in the lab-scale furnace experiment.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Size</th>
<th>Fixed carbon</th>
<th>Volatile matter</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>(-74 \text{ mm} 80%)</td>
<td>80.6</td>
<td>11.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>

#### Table 3. Composition of the reducing gas used in Case2-1 and 2-2.

<table>
<thead>
<tr>
<th>Gas species</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>% 48</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>% 3</td>
</tr>
<tr>
<td>Methane</td>
<td>% 37</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>% 12</td>
</tr>
</tbody>
</table>
lance tip in the lab-scale furnace. $\eta_{\text{PC}}$ in Case2-1 and 2-2 were about 20% higher than that in Case1. This difference could be caused by the differences in the blast temperature, the oxygen content in the blast, and the reducing agents injected from the lance. The blast temperature in Case1 was higher by 250 K than that in Case2-1 and 2-2. Higher blast temperature can improve $\eta_{\text{PC}}$. On the other hand, since the oxygen contents in the blast in Case2-1 and 2-2 were higher by 10% than that in Case1, so Case 2-1 and 2-2 had better condition for raising $\eta_{\text{PC}}$ from the aspect of oxygen content. Further, while we only injected PC in Case1, we co-injected reducing gas with PC in Case 2-1 and 2-2. Co-injection of reducing gas with PC accelerates the combustion of PC by accelerating heating of PC by the combustion heat of reducing gas, whereas the combustion of PC can also be suppressed by the separation of PC from oxygen and by the consumption of oxygen caused by the combustion of reducing gas. Figure 5 shows trends of the temperature of PC particles over the distance from the lance tip. In this study, the temperature of PC particles was rapidly raised by co-injection of reducing gas, suggesting that the rapid heating was the dominant factor for raising $\eta_{\text{PC}}$ in comparison with the two other effects. We concluded that $\eta_{\text{PC}}$ in Case2-1 and 2-2 were higher than that in Case1 because the effect of rapid heating of PC particles by co-injecting reducing gas overwhelmed the effect of higher blast temperature.

**Figure 6** shows example of the results of the spectroscopic measurement of PC combustion flame. Every chemi-luminescence spectrum of the PC combustion flame was composed of two components. The first one was a set of several chemi-luminescence peaks originating from hydrocarbon radicals and ash elements in PC, which appeared due to the PC combustion. The second one was a broad spectrum around 500 nm originating from thermal radiation of PC and inner wall of the furnace. **Table 4** is a list of major radicals and elements whose chemi-luminescence peaks appeared in the measured spectra and those peak positions in wavelength. In the spectra of PC combustion flame, chemi-luminescence peaks of OH and CH radicals, Na, and K appeared. We focused on these four chemi-luminescence peaks and evaluated the correlation between the intensity of the chemi-luminescence peaks and $\eta_{\text{PC}}$.

**Figure 7** shows a schematic diagram of explaining the calculation method of the chemi-luminescence peak intensity. We calculated the intensity of thermal radiation at the peak wavelength by linear approximation of the spectrum around the peak, and defined the intensity of chemi-luminescence peak as the subtraction of the intensity of the thermal radiation from the whole emission intensity.

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**Table 4.** A list of major radicals and elements whose chemi-luminescence peaks were detected in the measured spectra and those wavelength of chemi-luminescence peaks.

<table>
<thead>
<tr>
<th>Radical species</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>310 nm</td>
</tr>
<tr>
<td>CH</td>
<td>389 nm</td>
</tr>
<tr>
<td>Na</td>
<td>589 nm</td>
</tr>
<tr>
<td>K</td>
<td>766 nm</td>
</tr>
</tbody>
</table>
Fig. 7. A schematic diagram of explaining the calculation method of the chemi-luminescence peak intensity.

Figures 8(a)–8(c) shows trends of the intensity of each chemi-luminescence peak over the distance from the lance tip. In Case2-2, a large amount of unburnt PC char was deposited in the second observation window from the upstream side and the deposited char made it difficult to carry out measurement at the second window. Therefore, measurement results at the third window were plotted. The trend of the peak intensity showed the local maximum at about 300 mm in Case1, while it showed gradual decrease in Case2-1. It is said that the chemi-luminescence peak intensity of radicals varies depending on the temperature and the amount of generated radicals. While PC only burnt in Case1, the enhancement of PC combustibility by the co-injection of reducing gas might make the local maximum position closer to the lance tip in Case2-1, and it caused the difference of the trend of peak intensity between the cases. Further, from the comparison of Figs. 4 and 8, we found the position where the intensity of chemi-luminescence peak reached the local maximum value at each case was in the region where $\eta_{PC}$ was less than 20%. Since the decomposition and combustion of volatile matter are the main reactions in the initial stage of PC combustion, the chemi-luminescence of the PC combustion flame could mainly originate from the combustion of volatile matter. Comparing the results of Case2-1 and 2-2, the intensities of the peaks observed in Case2-2 were about one fourth of that in Case2-1, while the relationships between the peak intensities and the distance from the lance tip showed a similar tendency. The particle size of PC has a negative correlation with $\eta_{PC}$. That is, the smaller the particle size is, the higher the PC combustibility and the intensities of chemi-luminescence peaks are. Therefore, the peak strength in Case2-2, in which coarse PC particles were mainly observed from the window, was lower than that of Case2-1, in which fine PC particles were mainly observed from the windows. The chemi-luminescence peak intensities plotted in Fig. 8 were the averaged results of 25 measurements. Figure 9

Fig. 8. Trends of the intensity of each chemi-luminescence peak over the distance from the lance tip. (a) Case1, (b) Case2-1, (c) Case2-2.

Fig. 9. Ratio of the standard deviation to the average value of the chemi-luminescence peak intensities of each chemical species in Case2-1.
shows the ratio of the standard deviation to the average value of the chemi-luminescence peak intensities of each chemical species in Case2-1. For each chemi-luminescence peak, the intensity ratio of standard deviation to average value was up to 10% or more, and in some cases, it approached 25%. We assumed that this intense fluctuation of the peak intensities was caused by the intermittent PC combustion flame due to the heterogeneous PC flow. Even in such a case, we assumed that the ratio among the amounts of generated chemical species didn’t change if the other conditions were maintained well. Therefore, to measure $\eta_{PC}$ by utilizing spectra of the PC combustion flame, we focused on the relationship between the ratio of the intensities of chemi-luminescence peak and $\eta_{PC}$, so that we could reduce the effect of heterogeneous PC flow on the measurement results.

Figure 10 shows trends of the chemi-luminescence peak intensity ratios among the 4 chemical species of interest over the distance from the lance tip. In Case1, when the distance from the lance tip became longer, the peak intensity ratio between hydrocarbon radicals monotonously increased, while those between hydrocarbon radicals and ash elements gradually decreased, and those between ash elements showed almost constant value. In Case2-1 and 2-2, the peak intensity ratios of OH radical to other chemical species showed gradual decrease over the distance from the lance tip, while the ratios of the combinations of the other species showed almost constant value. Based on these results and the fact that PC is a kind of hydrocarbon, we prepared formulae for the estimation of $\eta_{PC}$ in each injection method by utilizing the chemi-luminescence peak intensity ratio between OH and CH radicals. Comparing Case2-1 and 2-2, we found that the peak intensity ratios for all combinations of chemical species showed similar values and trends. Therefore, we concluded that the direction in which PC combustion flame was observed didn’t affect the ratio among measured chemi-luminescence peak intensities. This is why we utilized the results of both Case2-1 and 2-2 for preparing the formula for $\eta_{PC}$ in co-injection of reducing gas with PC.

Figure 11 shows relationships between $\eta_{PC}$ and the ratio...
between chemi-luminescence peak intensity of OH radicals and that of CH radicals. We observed correlations between $\eta_{PC}$ and the peak intensity ratio. We used the ratio of the peak intensity of OH radical to that of CH radical in Case1, and in Case2-1 and 2-2, we used the reciprocal of the ratio used in Case1. The generating mechanisms of CH and OH radicals could be different among the cases because of several reasons. For example, the conditions of the PC combustion flame were different, the oxygen content in blast was higher in Case2-1 and 2-2 than in Case1, and the reducing gas blown in Case2-1 and 2-2 contained a large amount of H$_2$. These differences might be why the correlation between $\eta_{PC}$ and the peak intensity ratio was reversed in Case 2-1, 2-2 comparing to that of Case1.

From these results, we prepared the formula for estimating $\eta_{PC}$ from the ratio of chemi-luminescence peak intensities of OH radicals and that of CH radicals in each case as the following equations.

\[ \text{Case1: } \eta_{PC} = 45.0 \times R_{OH/CH} \tag{7} \]

\[ \text{Case2: } \eta_{PC} = 56.9 \times R_{CH/OH} \tag{8} \]

where $R_{ij}$ was the ratio of the chemi-luminescence peak intensity of $i$ to the chemi-luminescence peak intensity of $j$. By using these equations, we can estimate $\eta_{PC}$ in a non-contact method.

3. Evaluation of the Accuracy of PC Combustibility Measurement Method at EBF

3.1. Experimental Conditions

In order to evaluate the accuracy of the formulae to estimate $\eta_{PC}$ developed in the lab-scale furnace, we conducted spectroscopic measurement at EBF and estimated $\eta_{PC}$ by the formulae. EBF is a small BF whose working volume is 12 m$^3$. EBF has 3 tuyeres, and each tuyere has 2 holes for lance insertion. A lance was inserted into the left hole of each tuyere to inject reducing agents. We can operate EBF with injecting PC and reducing gas through the lance at each tuyere.

**Figure 12** shows a schematic diagram of the measurement configuration at EBF. We carried out the measurement from the right hole at No.1 tuyere. In the measurement, we installed a quartz window at the outlet of the hole, and fixed a measurement apparatus to the window. We made the measurement apparatus by fixing a finder scope, an optical probe and a beam splitter to an aluminum plate. The light from the inside of tuyere was divided into 30% to the finder scope side and 70% to the probe side by the beam splitter. We adjusted the measurement position with looking into the inside of the tuyere through the finder scope. We used the probe whose focal length was 2 300 mm. It was equal to the distance from the probe to PC combustion flame inside the tuyere. We focused to the point on the axis of the lance and 150 mm away from the lance tip. We connected the probe to the spectrometer by means of optical cable. We used the same spectrometer for the measurement as that in the lab-scale furnace, and we also measured the chemi-luminescence spectra of PC combustion flame in the same wavelength range.

**Table 5** is a list of averaged operational data at the No. 1 tuyere of EBF during the measurement. As reducing

<table>
<thead>
<tr>
<th>Unit</th>
<th>CaseA</th>
<th>CaseB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast volume Nm$^3$/h</td>
<td>414</td>
<td>298</td>
</tr>
<tr>
<td>O$_2$ enrichment %</td>
<td>28.8</td>
<td>36.4</td>
</tr>
<tr>
<td>Blast temp. degC</td>
<td>990</td>
<td>967</td>
</tr>
<tr>
<td>PC injection rate kg/h</td>
<td>59</td>
<td>55</td>
</tr>
<tr>
<td>COG injection rate Nm$^3$/h</td>
<td>–</td>
<td>38</td>
</tr>
</tbody>
</table>
agents, we injected only PC in CaseA, while we injected co-injected COG with PC in CaseB. In each case, we adjusted the theoretical flame temperature at the tuyere tip to the constant value by means of changing the content of oxygen in the blast. In each case, we intermittently carried out the spectroscopic measurements for 2 days, and the number of the measurements totaled about 50 times.

3.2. Experimental Results at EBF

Figure 13 shows the spectrum of PC combustion flame in the case of PC only injection. In the spectra of CaseA, we couldn’t find the chemi-luminescence peaks of OH radicals (around 310 nm) and CH radicals (around 389, 431 nm). In the lab-scale furnace, we found those peaks in Case1 when the blast temperature was 1523 K, while we couldn’t find those when the blast temperature was 1273 K. The blast temperature in CaseA was 1263 K. Therefore, we predicted that the heating of PC was delayed due to the low blast temperature, and it caused that the emission and combustion of volatile matter in PC didn’t sufficiently progress at the point we focused on. That may be why we couldn’t find the chemi-luminescence peaks of OH and CH radicals in CaseA. From these results, we estimated that $\eta_{PC}$ in CaseA was 0% at the point we focused on.

Figure 14 shows the spectrum of PC combustion flame in the case of co-injection of COG with PC. In CaseB, the spectrum of PC combustion flame was similar to the spectrum of Case2-1, while the absolute intensities of the chemi-luminescence peaks were different from those in the lab-scale furnace. That is, we found the chemi-luminescence

![Spectra of PC combustion flame in the cases of co-injection of COG with PC.](image)
peaks of OH (around 310 nm) and CH radical (around 389 nm). Using these chemi-luminescence peak intensities, we estimated $\eta_{PC}$ in CaseB.

Figure 15 shows schematic diagrams of differences in the measurement configuration between the lab-scale furnace and EBF. The existence of the beam splitter, the focal length of the optical probe, the observation direction of combustion flame, and the distance from PC combustion flame to the probe were the differences. We had already confirmed that the observation direction of combustion flame had no effect on the chemi-luminescence peak intensity ratio in the lab-scale experiment. On the other hand, the other three differences seemed to affect the peak intensity ratio. Therefore, prior to the estimation of $\eta_{PC}$, we evaluated the effects of the differences on the peak intensity ratio, and calculated the correction factors if there was any effect.

At first, we evaluated the effect of the beam splitter. The beam splitter used in the measurement in EBF had different light transmittance at each wavelength where the chemi-luminescence peaks of OH and CH radicals appeared. Therefore, we calculated the effect of the beam splitter on the ratio of the chemi-luminescence peak intensity of OH and CH radicals from the transmittance of the beam splitter at each wavelength, as shown in the Eq. (9).

$$R_{\text{CH/OH,EBF}} = 0.968$$

where $R_{\text{CH/OH,EBF}}$ was the ratio of the chemi-luminescence peak intensity of the CH radical to that of the OH radical measured in EBF.

Next, we evaluated the effect of the focal length of the probe and that of the distance from the PC combustion flame to the optical probe. In order to evaluate those effects on the spectra of the flame, we carried out the following experiments. We installed the probe and the standard light source at a fixed distance under the conditions corresponding to each measurement configuration, and measured the spectrum of the standard light source. We used the same probes as those used in the lab-scale furnace and EBF for this experiment. We used L7810-03 (made by Hamamatsu Photonics) as the standard light source. Figure 16 shows measured spectra of the standard light source under each measurement configuration. We found that the difference of the measurement conditions affected the measured spectra of the light from the standard light source. Therefore, we calculated the correction factor from the experimental results as in the Eq. (10), and corrected the ratio of the chemi-luminescence peak intensities of OH and CH radicals measured in EBF.

$$R_{\text{CH/OH}} = 1.545$$

We determined the formula for estimating $\eta_{PC}$ in CaseB from the Eq. (8) prepared in the lab-scale furnace and the correction of the ratio of peak intensity by the Eqs. (9) and (10) as shown in the Eq. (11).

$$\eta_{PC,EBF} = 85.1$$

where $\eta_{PC,EBF}$ was PC combustibility in EBF. We calculated $R_{\text{CH/OH,EBF}}$ from the measured spectra in Case B, and calculated $\eta_{PC,EBF}$ by using the Eq. (11). We calculated $R_{\text{CH/OH,EBF}}$ from every 49 measured results in Case B, and used the average of 49 values of $R_{\text{CH/OH,EBF}}$ for the calculation of $\eta_{PC,EBF}$.

Figure 17 shows trends of $\eta_{PC}$ and $\eta_{PC,EBF}$ over the distance from the lance tip. From the comparison between Case1 and CaseA, we confirmed that the combustion of PC might have not started in the measurement position which was 150 mm away from the lance tip, and the value of $\eta_{PC,EBF}$ in CaseA (0%) was reasonable. In CaseB, the value of $\eta_{PC,EBF}$ was 11.6%. That value had also good agreement with the change of $\eta_{PC}$ in Case2-1 and 2-2. The reported values of PC combustibility in the previous study was higher than $\eta_{PC,EBF}$ in CaseB, but the measurement of PC combi-
bustibility in the previous study was conducted at a location farther from the lance tip than that in Case B of this study. This can be why $\eta_{PC,EBF}$ in Case B showed the lower value than that in the previous study.

From these results, we confirmed that the same correlation between PC combustibility and the ratio of CH peak intensity and OH peak intensity also existed in BF under operation as in the lab-scale furnace. Then, we were able to estimate PC combustibility in BF under operation without bothering BF operation, by using the formula prepared in the lab-scale furnace. That is, we have achieved the development of the non-contact in-situ measurement method of PC combustibility. The applicability of this method to operations with different conditions of PC and reducing gas injection will be studied in the future.

4. Conclusion

In this study, we conducted the combustion experiment in the lab-scale furnace to develop the non-contact measuring method of PC combustibility. After that, we measured PC combustibility in EBF by the developed method to ensure the accuracy of the method. In these experiments, we found three main results shown below.

1) In PC combustion experiment in the lab-scale furnace, we measured chemi-luminescence spectra of the PC combustion field, and detected the chemi-luminescence peaks originating from hydrocarbon radicals and ash elements. Through the analysis of these chemi-luminescence peaks, we found that the correlation between PC combustibility and the ratio of peak intensity of OH radicals to that of CH radicals.

2) From the results in the lab-scale furnace, we prepared the formulae for estimating PC combustibility from the ratio between chemi-luminescence peak intensity of OH radicals and that of CH radicals. Then we estimated the PC combustibility in COURSE50 EBF from the measured spectrum of PC combustion flame in EBF. As a result, in both condition of only PC injection and co-injection of COG with PC, we confirmed that the estimated value of PC combustibility in EBF agreed well with the result in the lab-scale furnace.

3) From these results, we concluded that the PC combustibility can be measured with non-contact method by utilizing the chemi-luminescence peak intensities of OH radicals and CH radicals in PC combustion flame.

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REFERENCES


Fig. 17. Trends of $\eta_{PC}$ and $\eta_{PC,EBF}$ over the distance from the lance tip.