Influence of Fuel-Moisture Content and Excess Air on Formation and Reduction of CO and NO in a Fluidized-Bed Combustor Fired with Thai Rice Husk

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Harvesting:

\[
\sim 20 \text{ million tons/yr}
\]

Rice husk availability:

\[
2.3–3.7 \text{ million tons/yr}
\]

Power generation potential from unused rice husk:

\[
234–375 \text{ MW}_{\text{el}}
\]
To investigate effects of the fuel-moisture content and operating conditions (excess air) on emission performance of a fluidized-bed combustor firing Thai rice husk.

To obtain empirical models (fitting equations) for predicting axial CO/CO$_{\text{max}}$ and NO$_x$/NO$_{x,\text{max}}$ profiles, which could be used for assessment of CO and NO$_x$ concentrations at different locations along the combustor height.
Materials and Methods
Conical Fluidized-bed Combustor (FBC)
Experimental Set-up with the Conical FBC
Experimental Set-up (General View)
Gas analyzer was used for measuring gas concentrations (NO, CO, O₂) in the tests.
The Fuel

Rice Husk
Ultimate Analysis $^a$ (wt.%) and Lower Heating Value (MJ/kg) of Rice Husk Used in the Experimental Tests

($W =$ fuel-moisture content, $A =$ fuel-ash content; $LHV =$ lower heating value)

<table>
<thead>
<tr>
<th>Series No.</th>
<th>$W^b$</th>
<th>A</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>LHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.0</td>
<td>12.99</td>
<td>34.19</td>
<td>4.86</td>
<td>36.60</td>
<td>0.32</td>
<td>0.04</td>
<td>12.34</td>
</tr>
<tr>
<td>2</td>
<td>16.8</td>
<td>12.15</td>
<td>31.97</td>
<td>4.54</td>
<td>34.21</td>
<td>0.30</td>
<td>0.03</td>
<td>11.37</td>
</tr>
<tr>
<td>3</td>
<td>24.9</td>
<td>10.96</td>
<td>28.85</td>
<td>4.10</td>
<td>30.88</td>
<td>0.27</td>
<td>0.03</td>
<td>10.02</td>
</tr>
<tr>
<td>4</td>
<td>35.5</td>
<td>9.42</td>
<td>24.78</td>
<td>3.52</td>
<td>26.52</td>
<td>0.23</td>
<td>0.03</td>
<td>8.25</td>
</tr>
<tr>
<td>5</td>
<td>40.2</td>
<td>8.73</td>
<td>22.98</td>
<td>3.27</td>
<td>24.59</td>
<td>0.22</td>
<td>0.02</td>
<td>7.47</td>
</tr>
</tbody>
</table>

$^a$ On “as-received” basis

$^b$ $W = 11\%$ is the moisture content in “as-received” fuel; in other tests (No. 2, 3, 4 and 5), the fuel-moisture content was secured by additional water.
Parameters Varied and Maintained in the Experimental Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fuel-moisture content (W)</td>
<td>11.0, 16.8, 24.9, 35.5 and 40.2 wt.%</td>
</tr>
<tr>
<td>2. Fuel feed rate (FR)</td>
<td>82.5–82.8 kg/h</td>
</tr>
<tr>
<td>3. Excess air (EA)</td>
<td>40, 60, 80 and 100%</td>
</tr>
<tr>
<td>4. Bed height (BH)</td>
<td>40 cm</td>
</tr>
</tbody>
</table>

Excess air was determined based on excess air ratio ($\alpha$) calculated using experimental $O_2$ and CO concentrations in dry flue gas at the cyclone exit:

$$\alpha = \frac{21}{21 - (O_2 - 0.5CO)}$$
Results and Discussion
Effects of the Fuel-Moisture Content on the Axial Temperature Profiles in the Conical FBC Firing Rice Husk at FR $\approx 82.6$ kg/hr for Different Excess Air Values

$EA \approx 40\%$

$EA \approx 100\%$

![Graph showing temperature profiles for different moisture contents and excess air values.](image-url)
Effects of the Fuel-Moisture Content on the Axial O$_2$ Concentration Profiles in the Conical FBC Firing Rice Husk at FR $\approx$ 82.6 kg/h for Different Excess Air Values

EA $\approx$ 40%

EA $\approx$ 100%
Effects of the Fuel-Moisture Content on the Axial CO Concentration Profiles in the Conical FBC Firing Rice Husk at FR $\approx 82.6$ kg/h for Different Excess Air Values

$EA \approx 40\%$

$EA \approx 100\%$
CO formation:

\[
C + CO_2 \rightarrow 2CO \\
C + OH \rightarrow CO + H \\
2C + O_2 \rightarrow 2CO
\]

CO reduction:

\[
2CO + O_2 \rightarrow 2CO_2 \\
CO + OH \rightarrow CO_2 + H
\]
Effects of the Fuel-Moisture Content on the Axial NO\textsubscript{x} Concentration Profiles in the Conical FBC Firing Rice Husk at FR \approx 82.6 kg/h for Different Excess Air Values

EA \approx 40\%

EA \approx 100\%
Chemical Reactions Related to NO Formation/Reduction in the Reactor

NO formation:
- \( \text{HCN} + \frac{1}{2}\text{O}_2 \rightarrow \text{NCO} \)
- \( \text{NCO} + \frac{1}{2}\text{O}_2 \rightarrow \text{NO} + \text{CO} \)
- \( \text{NH}_3 + \frac{5}{4}\text{O}_2 \rightarrow \text{NO} + \frac{3}{2}\text{H}_2\text{O} \)

NO reduction:
- \( \text{NO} + \text{CO} \rightarrow \frac{1}{2}\text{N}_2 + \text{CO}_2 \)
- \( \text{NO} + \text{C} \rightarrow \frac{1}{2}\text{N}_2 + \text{CO} \)
- \( \frac{2}{3}\text{NH}_3 + \text{NO} \rightarrow \frac{5}{6}\text{N}_2 + \text{H}_2\text{O} \)
Modeling $CO_{\text{max}}$ and $NO_{x,\text{max}}$ in the Conical FBC Firing Rice Husk

$CO_{\text{max}}$ (g/m$^3$, in wet flue gas under standard conditions) was found to depend on the excess air ratio, $\alpha$, bed temperature, $T_{\text{bed}}$, as well as fuel-moisture, $W$, and fuel-ash, $A$, contents in “as-received” fuel:

$$CO_{\text{max}} = 5.7 \times 10^6 \alpha^{-2} A^{1/3} W^{1/2} T_{\text{bed}}^{-2} \quad (R^2 = 0.934)$$

However, $NO_{x,\text{max}}$ as $NO_2_{,\text{max}}$ (g/m$^3$, in wet flue gas under standard conditions) was apparently affected by three variables, fuel-N content (in “as-received” fuel), excess air ratio and bed temperature:

$$NO_{x,\text{max}} = 4.5N(0.4 - 0.1N) \alpha^{0.5} \left( \frac{T_{\text{bed}} - 800}{1000} \right)^{0.15} \quad (R^2 = 0.855)$$
Predicted and Experimental \( \text{CO}_{\text{max}} \) and \( \text{NO}_{x,\text{max}} \) Versus Excess Air for Firing Thai Rice Husk with Variable Fuel-Moisture Content in the Conical FBC

**CO\(_{\text{max}}\)**

**NO\(_{x,\text{max}}\)**

![Graphs showing CO\(_{\text{max}}\) and NO\(_{x,\text{max}}\) versus excess air with predicted and experimental data for different fuel-moisture contents.](image-url)
The fitting equation for the axial CO/CO$_{\text{max}}$ profile was found to be:

- for 40% and 60% EA, $0.5 \leq X/X_{\text{CO,max}} \leq 3.5$:

\[
\frac{\text{CO}}{\text{CO}_{\text{max}}} = X_0^{1.72} \exp \left[ 1 - X_0^{(1.61 - 0.12X_0)} \right] \quad (R^2 = 0.940)
\]

- for 80% and 100% EA, $0.4 \leq X/X_{\text{CO,max}} \leq 2.6$:

\[
\frac{\text{CO}}{\text{CO}_{\text{max}}} = X_0^{1.68} \exp \left[ 1 - X_0^{(1.70 - 0.02X_0)} \right] \quad (R^2 = 0.845)
\]

where $X_0 = X/X_{\text{CO,max}}$. 
Relative CO Concentration Profiles in the Conical FBC Firing Rice Husk

Predicted by Eq.(3)  
Predicted by Eq.(4)
For $0.7 \leq X/X_{NOx,max} \leq 3.2$, the fitting equation for the axial NO$_x$/NO$_{x,max}$ profile was represented by a single correlation:

$$\frac{NO_x}{NO_{x,max}} = Z_0^{1.05} \exp\left[1 - Z_0^{(1.07 - 0.05Z_0)}\right]$$

$(R^2 = 0.974)$

where $Z_0 = X/X_{NOx,max}$. 
Relative NO\textsubscript{x} Concentration Profiles in the Conical FBC Firing Rice Husk

![Graph showing relative NO\textsubscript{x} concentration profiles for different fuel moisture contents (W) and excess air (EA) ratios. The graph includes data points predicted by Eq. (2).]
By increasing the fuel-moisture content from 11% (“as-received” basis) to 35.5%, the bed temperature in the conical FBC firing rice husk can be diminished by 130–150°C, which results in mitigation of NO\textsubscript{x} formation in the fluidized bed region, with the respective reduction in the NO\textsubscript{x} emissions from the combustor. However, this result is accompanied by elevated CO emissions from the reactor.

All axial CO and NO\textsubscript{x} concentration profiles have the maximums, CO\textsubscript{max} or NO\textsubscript{x, max} (as NO\textsubscript{2, max}), at corresponding heights, X\textsubscript{CO, max} or X\textsubscript{NOx, max}, respectively, and these peak concentrations in the fluidized bed are affected by both the fuel quality and excess air ratio with different extents.
Empirical correlations (or empirical models) for \( CO_{\text{max}} \) or \( NO_{x,\text{max}} \) (as \( NO_2_{,\text{max}} \)) are proposed in this work, both including the effects of fuel properties and operating conditions.

Relative axial profiles, \( CO/CO_{\text{max}} = f(X/X_{\text{CO, max}}) \) and \( NO_{x}/NO_{x,\text{max}} = f(X/X_{\text{NOx, max}}) \), in the conical FBC can be readily approximated by fitting equations (or empirical models) at \( R^2 = 0.84-0.97 \). While \( CO_{\text{max}} \) and \( NO_{x,\text{max}} \) are determined by the above empirical models, reliable correlations for \( X_{\text{CO, max}} \) and \( X_{\text{NOx, max}} \) should be determined with the aim to support the models for the relative axial CO and NO\(_x\) concentration profiles.
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Thank You!