Least-cost NO\textsubscript{x} Emissions Control in a Fluidized-bed Combustor Fired with Rice Husk

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Abstract: This paper presents experimental results on firing Thai rice husk in a conical fluidized-bed combustor (FBC) when using two least-cost NO\textsubscript{x} emissions controlling techniques: (1) air-staging, and (2) adding water to “as-received” rice husk. Experimental tests were carried out on a 400 kW\textsubscript{th} laboratory-scale prototype performing high combustion efficiency of rice husk. In the first test series, the combustor was operated on “as-received” rice husk with the fuel-moisture content 7.3% fired at 80 kg/h feed rate and total excess air of about 57%, for three values of the secondary-to-total air ratio (S/T), 0, 0.2 and 0.4. In the second test series, rice husk with different fuel-moisture contents (18.4%, 28.0% and 38.2%) was burned for S/T = 0, at almost the same combustor load and total excess air as in the first test series. In all the tests, temperature and gas concentrations (O\textsubscript{2}, CO and NO\textsubscript{x}) were measured in the conical FBC (along the combustor height), as well as in the stack flue gas. Both air staging and variation in the fuel-moisture content were found to have substantial effects on the axial CO and NO\textsubscript{x} concentration profiles. Meanwhile, the NO\textsubscript{x} emissions from the conical FBC reduced by about 15% when increasing S/T from 0 to 0.4, while the CO emission increased significantly (by 67%). By increasing the fuel-moisture content from 7.3 to 38.2%, the NO\textsubscript{x} emissions were reduced by about 15%, while the CO emission increased by about 40%.

Keywords: Air-staging Combustion, Biomass Combustion, CO Emission, Moisture Content, NO\textsubscript{x} Emissions

1. INTRODUCTION

In Thailand, rice is an important product cultivated on a large scale. Annually, about 20 million tons of rice are produced in this country. Rice husk, an outer cellulose layer of rice grains, is a residue from the rice milling process, accounting for up to 23% of total rice weight. Based on 50–80% harvest collectivity, the available amount of rice husk is estimated to be 2.3 to 3.7 million tons per year. Taking into account such significant availability and substantial higher heating value of this agricultural residue, about 14 MJ/kg (on average), rice husk is considered to be one of the most viable biomass fuels in Thailand [1].

Like firing of any other biomass fuel, the combustion of Thai rice husk is accompanied by substantial NO\textsubscript{x} and CO emissions the rates of those are influenced by fuel properties, operating conditions and design features of a combustion system, or by the combustion method [2–9]. While the CO emission is basically controlled by air supply (at sufficient level), the strategy of the NO\textsubscript{x} emissions control is based on diminishing of the temperature and oxygen concentration in the zone of active fuel oxidation, the key factors affecting the fuel-NO formation mechanism. As the air supply may have opposite effects on NO\textsubscript{x} and CO formation, simultaneous monitoring of both emissions from a combustion system is required.

During recent decades, the least-cost primary measures of the above strategy, such as lowering excess air, air-staging, fuel-staging (or reburning) and water/steam injections into the flame, have been developed and implemented on boiler furnaces firing fossil fuels (pulverized coals, fuel oil, natural gas) with the aim to reduce NO\textsubscript{x} emissions from power generation units. Some of these measures have been tested on fluidized bed combustors and stokers firing biomass fuels [3, 10–11]. As revealed by experimental studies on grate-firing systems (stokers) fueled with wood residues and using air-staging, NO\textsubscript{x} emissions can be reduced by up to 50% [10], while higher, up to 80%, efficiency of the NO\textsubscript{x} reduction, are achievable in a grate-firing system with two understokers, combining fuel-staging and air-staging techniques [11].

Another least-cost technique for mitigation of NO\textsubscript{x} emissions, through adding water to “as-received” fuel, has been proved on a fluidized-bed combustor firing wood sawdust. For the particular value of excess air, with increasing the fuel-moisture content from about 16 to 34%, the NO\textsubscript{x} emissions from the combustor are reported to reduce by about 25%, while the CO emission increased 3–5 times [4]. It should be noted that such elevated CO concentrations along over the gas path may lead to the higher rate of NO\textsubscript{y} decomposition (by reaction of NO with CO on the surface of chars), which contributes to the reduction of NO\textsubscript{x} emissions from a fluidized-bed combustion system together with lowering of the bed temperature [4, 5,12].

Compared to other viable Thai biomass fuels (sawdust and pre-dried sugar cane bagasse) fired under similar operating conditions, the fluidized bed combustion of Thai rice husk is generally characterized by higher emissions of NO\textsubscript{x} and CO [2]. However, there is a lack of data on the effects of various NO\textsubscript{x} controlling measures for fluidized-bed combustion of rice husk. As this combustion method does not promote fuel staging, this work was focused on two least-cost measures only, (1) air-staging, and (2) adding water to “as-received” fuel, which, as expected, would lead to reduction of NO\textsubscript{x} emissions from a fluidized bed combustor firing rice husk.

The effects of operating conditions and fuel properties on the combustion and emission characteristics of the reactor for air-staging combustion of “as-received” Thai rice husk, as well as on those for conventional combustion of the rice husk with the variable fuel-moisture content, were the main objectives of this work.

2. METHODOLOGY

2.1 Experimental set-up

Experimental tests were carried out on a 400 kW\textsubscript{th} laboratory-scale prototype of a conical fluidized-bed combustor (conical FBC). Fig. 1 shows the schematic diagram of the experimental set-up with this combustor consisting of two parts: a cylindrical section (with 1m inner diameter and 3 m height) and a conical section (with a 40°cone angle and 1 m height). The combustor body was externally insulated with the 50-mm ceramic-fiber material for minimizing heat losses across the combustor’s walls.

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Silica sand of 0.3–0.5 mm particle size was used as the inert bed material to ensure the bubbling fluidization mode in this conical FBC [4–5]. In all combustion tests, the static bed height of the bed material was secured at the same value (40 cm). The conical FBC was equipped with a screw type feeder supplying rice husk over the bed at a 0.65-m level above the air distributor.

A 25 hp blower supplied primary combustion air (under ambient conditions) through the air distributor located at the bottom of the conical part while the secondary air was injected tangentially into the freeboard region at a 1.65 m level above the air distributor.

A “Testo-350” gas analyzer was employed for monitoring gas concentrations (for O₂, CO, NOₓ) along the combustor height, as well as at the exit of an ash-collecting cyclone installed downstream from the combustor exit, as seen in Fig. 1. Chromel-alumel thermocouples (of type K) were fixed at different levels along the combustor height and at the cyclone exit for measuring the temperature at these locations.

### 2.2 Fuel properties

Proximate and ultimate analyses and lower heating value of rice husks used in the combustion tests with (1) air-staging and (2) variable fuel-moisture content are shown in Table 1. As seen in Table 1, “as-received” rice husk with the fuel-moisture content MC = 7.3% was burned in the combustion tests for air-staging. However, for the second series of the tests at higher fuel-moisture contents (secured by adding corresponding amounts of water to the “as-received” rice husk), Table 1 provides the proximate and ultimate analyses on “as-fired” basis. The fuel properties on “as-fired” basis were calculated by using the properties on “as-received” basis (i.e. for Sample 1 in Table 1) and taking into account actual values of the fuel-moisture content [13].

The fuel lower heating value for Samples 1–4 (see Table 1) was estimated by Ref. [13] using the fuel ultimate analysis.

### Table 1 Proximate and ultimate analyses and lower heating value (LHV) of Thai rice husk used in the combustion tests with air-staging and variable fuel-moisture content

<table>
<thead>
<tr>
<th>Fuel analysis</th>
<th>Test series for air-staging: (wt.%,”as-received” basis)</th>
<th>Tests series for variable fuel-moisture content: (wt.%,”as-fired” basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample 1</td>
<td>Sample 2</td>
</tr>
<tr>
<td>Proximate analysis:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>7.30</td>
<td>18.4</td>
</tr>
<tr>
<td>Ash</td>
<td>15.7</td>
<td>13.8</td>
</tr>
<tr>
<td>Ultimate analysis:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>42.82</td>
<td>37.69</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.45</td>
<td>3.92</td>
</tr>
<tr>
<td>Oxygen</td>
<td>29.38</td>
<td>25.86</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.37</td>
<td>0.33</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>15.71</td>
<td>13.53</td>
</tr>
</tbody>
</table>
2.3 Operating conditions

The runs of the first test series were conducted at different values of the secondary-to-total air ratio (S/T), 0, 0.2 and 0.4, while the fuel feed rate and total excess air were adjusted at about FR = 80 kg/h and EA ≈ 57%, respectively. In these test runs, rice husk of a single (“as-received”) fuel analysis was burned, as indicated in Table 1.

In the second test series, rice husk with different fuel-moisture contents (18.4%, 28.0% and 38.2%, as given in Table 1) was burned conventionally (S/T = 0), at almost the same load (fuel feed rate) and total excess air as in the first test series.

3. RESULTS AND DISCUSSION

3.1 Air-staged combustion

Fig. 2 shows the axial temperature and O₂, CO and NOₓ concentration profiles in the conical FBC for the first test series at variable S/T. As revealed by the experimental results, the axial temperature profiles (see Fig. 2a) were rather uniform and weakly dependent on S/T. However, for the staged combustion at S/T = 0.2, the temperatures at all locations along the combustor height were slightly higher than those for firing this rice husk at S/T = 0.4 and S/T = 0.

As seen in Fig. 2b, the axial O₂ concentration profiles showed quite strong effects of the secondary air injection. While the O₂ concentration for the conventional combustion reduced gradually along the combustor height, the axial O₂ concentration profiles for the staged combustion showed the local O₂ maximums in the vicinity of air injection. Two factors indicated apparently the highly intensive heat-and-mass transfer in this fluidized bed combustor, (1) independence of the axial temperature gradient from S/T in the vicinity of air injection (when the secondary air with the ambient temperature was injected into hot flue gas) and (2) increase in the O₂ concentration at the locations prior to the secondary air injection. Unlike the conventional combustion occurring mainly in the fluidized bed region (0–1 m heights above the air distributor), the air staging led to oxidation of some amount of biomass fuel in the freeboard region, as followed from the analysis of the axial temperature and O₂ concentration profiles for this test series.

Due to lowered O₂ concentrations in the fluidized bed region for the staged combustion, the maximum CO concentration (CO max) in the flue gas increased significantly with higher S/T and attained about 4.5% at S/T = 0.4, as may be seen in Fig. 2c. This fact could be explained by reduction in the rate of CO decomposition (through its homogeneous oxidation by O₂) in the fluidized bed region. Compared with the conventional combustion, when the CO concentrations dropped down to negligible values at the combustor top, the air staging led to the elevated CO concentrations in the freeboard region as well as at the cyclone exit, or eventually, to the elevated CO emissions from this conical FBC.

Fig. 2 Effects of air-staging on the axial temperature (a), O₂ (b), CO (c) and NOₓ (d) concentration profiles in the conical FBC firing “as-received” rice husk at FR = 80 kg/h and EA ≈ 57%
In this work, quite small NO₂ concentrations (1–2 ppm) were found in the tests; hence, NO₂ emissions were represented by NO only.

For the temperature level in this combustor (see Fig. 2a), NO₂ emissions were expected to form via the fuel-NO formation mechanism. This fact could explain significant effects of S/T on the axial NOₓ concentration profiles. Indeed, in accordance with this mechanism, fuel-NO is basically formed in the fluidized bed region, through oxidation of nitrogenous species, such as HCN and NH₃, resulting from the devolatilization process occurring in this region [8–11, 14]. Hence, with the reduction of (local) excess air in the fluidized bed region, the rate of fuel-NO formation is expected to be lower.

As seen in Fig. 2d, through the air-staged combustion (at S/T = 0.2 and S/T = 0.4), it was managed to mitigate the NOₓ formation rate in the fluidized bed region. Because of the reduction in the O₂ concentrations in this region (caused by diminishing the primary air supply), the maximum NOₓ concentration (NOₓ,max) in the flue gas reduced by some 30% for S/T = 0.2 and by 45% for S/T = 0.4 compared to that for the conventional combustion at similar total excess air.

For the three S/T values, the gradual reduction of the NOₓ concentration along the combustor height observed in the freeboard region up to the level of the secondary air injection (see Fig. 2d). This NOₓ reduction likely occurred through reactions of NO with char-C and CO (on the char surface) and, also, through homogeneous reaction with NH₃ (at the oxygen deficiency) [8,9]. However, in the runs with air staging, some increase in the NOₓ concentration in the flue gas was observed downstream from the plane with secondary air nozzles. Nevertheless, by increasing S/T, the NOₓ concentration at the combustor top was somewhat lowered.

Fig. 3 shows the CO and NOₓ emissions (corrected to the 7% O₂ dry flue gas), i.e. CO and NOₓ concentrations in the flue gas at the cyclone outlet, for the first test series. While the CO emission increased substantially following the increase in S/T, the NOₓ emissions from the conical FBC were noticeable reduced with implementation of the stage combustion. As revealed by the experimental results in Fig. 3, the NOₓ emissions reduced by about 15% (from 148 ppm for conventional combustion to 126 ppm at S/T = 0.4), while the CO emission increased by 67%, from 127 ppm (for S/T = 0) to 385 ppm (for S/T = 0.4). As the NOₓ concentrations at the combustor top were close values, the above NOₓ reduction was likely achieved via catalytic (heterogeneous) reaction of NO with CO in the cyclone securing the relatively long residence time for the reactants. This fact along with the significant rate of NOₓ reduction in the freeboard region (prior to secondary air injection) indicated the relatively high catalytic ability of the rice husk fly ash.

3.2 Conventional fluidized bed combustion of rice husk with variable fuel-moisture content

Fig. 4 shows the same, as in Fig. 2, thermal and emission characteristics of the conical FBC for the second test series, i.e. for the conventional combustion of rice husk of a single fuel analysis (on “dry” basis), for different fuel-moisture contents (on “as-fired” basis). In these test runs, the EA values (at about 65%) were somewhat higher than those in the tests with air-staging.

Compared to the experimental results for conventional combustion of “as-received” rice husk, the temperatures at all the locations in the combustor volume reduced sensibly with increasing the fuel-moisture content. However, the axial temperature profiles (see Fig. 4a) for higher fuel-moisture contents saved the uniformity along the combustor height.

As may be concluded based on data in Fig. 4b, the rate of O₂ consumption (or the fuel oxidation rate) in the fluidized bed region was lowered with higher fuel-moisture contents due to, primarily, the reduction in the bed temperature affecting the rate of devolatilization as well as oxidation of combustible volatiles in this region [8].

In all the runs of this test series, a substantial increase in the CO concentration (including CO_{max}) was observed in the bed region for the higher values of MC (see Fig. 4c), mainly owing to the increased contribution of “wet” oxidation of char-C to CO [4]. Meanwhile, in the freeboard region of the combustor, where CO was oxidized in homogeneous reactions with (excess) oxygen and OH radicals [2], gradual reduction in the CO concentration was observed along over the combustor height. Because of the elevated concentration of water vapor (and, accordingly, OH radicals), the highest rate of the CO oxidation in the combustor’s freeboard region was observed in the test run at highest fuel-moisture content, MC = 38.2%. As the results, the CO concentrations at the combustor’s top were quite close for different values of MC.

Like for CO, the axial NOₓ concentration profiles (see Fig. 4d) were significantly affected by the fuel-moisture content. Because of the reduction in the bed temperature, the NOₓ concentration (including NOₓ,max) lowered with higher values of MC. As found in this test series, switching the fuel from “as-received” rice husk to the high-moisture rice husk with MC = 38.2% led to the NOₓ,max reduction by about 60%.

Fig. 3 Effects of air-staging on NOₓ and CO emissions from the conical FBC firing “as-received” rice husk at FR = 80 kg/h and EA = 57%
However, in the freeboard region with the above processes of NO reduction, the effects of fuel-moisture content became quite weak, leading, eventually, to close values of NOx concentrations (for different values of MC) at the top of the conical FBC.

The effects of the fuel-moisture content on the CO and NOx emissions (on 7% O2 in dry gas basis) from the conical FBC firing rice husk at excess air about 60% and fuel feed rate 80 kg/h are shown Fig. 5. Despite quite close values of CO and NOx concentrations at the top of the combustor fueled with rice husk at different values of MC, the dependencies of CO and NOx emissions varied apparently with respect to the fuel-moisture content. This effects could be likely explained by two processes occurred in the ash-collecting cyclone, (1) the "wet" oxidation of char-C leading to CO formation and, on the contrary, (2) the ash-catalyzed NO decomposition through the reaction with this CO in the cyclone. Note that these processes proceeded at relatively low temperatures in the non-insulated cyclone.

![Fig. 4](image)

Fig. 4 Effects of the moisture content in fuel on the axial temperature (a), O2 (b), CO (c) and NOx (d) concentration profiles in the conical FBC firing rice husk at FR = 80 kg/h and EA ≈ 65%

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![Fig. 5](image)

Fig. 5 Effects of the moisture content in fuel on NOx and CO emissions from the conical FBC firing rice husk at FR = 80 kg/h and EA ≈ 65%
As seen in Fig. 5, water injection into the “as-received” Thai rice husk (prior to its firing in a fluidized bed), resulted in the 15% reduction of NO\textsubscript{x} emissions from the conical FBC, from 151 ppm for MC = 7.3% (in “as-received” fuel) to 129 ppm for MC = 38.2%, while the CO emission increased by about 40%, from 130 ppm to 216 ppm, respectively.

4. CONCLUSIONS

Two least-cost NO\textsubscript{x} emissions controlling techniques, air-staging and adding water to “as-received” fuel, were experimentally tested on a 400 kW\textsubscript{th} laboratory-scale prototype with the conical fluidized-bed combustor (FBC) firing Thai rice husk at similar major operating conditions (fuel feed rate and total excess air). In all the test runs, the fuel feed rate was maintained at about 80 kg/hr, while excess air was adjusted at about 57% in the tests for air-staging and 65% in the tests for firing variable-moisture fuel.

The following general conclusions can be derived from this experimental work:

- both air-staging and firing rice husk with the variable fuel-moisture content results in substantial effects on the axial CO and NO\textsubscript{x} concentration profiles in the conical FBC;
- despite significant effects of both air-staging and fuel-moisture content on the maximum of CO and NO\textsubscript{x} concentrations (occurring in the fluidized bed region), these concentrations at the combustor’s top turned out to be close for different secondary-to-total air ratios (in the tests with air-staging) and fuel qualities (in the tests with variable fuel-moisture content).
- with implementation of air-staged combustion, the NO\textsubscript{x} emissions from this conical FBC can be reduced by 15% (from 148 ppm to 126 ppm, on 7% O\textsubscript{2} dry gas basis) through switching from the conventional combustion to the one with air-staging at the secondary-to total air ratio of 0.4; however, the CO emission is expected to increase by 67% remaining, nevertheless, at the level below 400 ppm for the applied operating conditions.
- by increasing the fuel-moisture content in Thai rice husk from 7.3 to 38.2%, the NO\textsubscript{x} emissions can be reduced by about 15%, while the CO emission is expected to increase by about 40% remaining below 250 ppm for the applied operating conditions.
- the NO\textsubscript{x} reduction reactions in the ash-collecting devices (through ash-based catalytic reaction of NO with CO) are important, as revealed by data from both test series; this fact along with the significant rate of NO\textsubscript{x} reduction in the freeboard region indicates the relatively high catalytic ability of the rice husk fly ash.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support from the Royal Golden Jubilee Ph.D. Program, the Thailand Research Fund (contracts PHD/0051/2546 and BGJ47K0006).

6. REFERENCES