Enhanced NO\textsubscript{x} Reduction by Combined Staged Air and Flue Gas Recirculation in Biomass Grate Combustion

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ABSTRACT: Flue gas recirculation (FGR) is a conventional means of reducing NO\textsubscript{x} emissions that involves lowering the peak flame temperature and reducing the oxygen concentration in the combustion region. Staged air combustion is also an effective means of NO\textsubscript{x} reduction, especially in biomass combustion. This article reports results on NO\textsubscript{x} emissions in a set of experiments combining FGR and staged air combustion in a grate-fired laboratory-scale reactor. Two different compositions of the recirculated flue gas were used: CO\textsubscript{2} and CO\textsubscript{2} + NO. The CO\textsubscript{2} concentration varied between 0–8 vol % of the total inlet flow rate and the NO concentration varied between 0 and 64 ppm. Two different FGR locations were also tested: above and below the grate. The results are compared with a reference experiment performed without FGR. The NO\textsubscript{x} reduction level from staged air combustion at the optimal primary excess air ratio is ∼70%, while employing FGR can reduce the NO\textsubscript{x} emissions by an additional 5%–10%. The optimal primary excess air ratio range is 0.9–1. However, FGR more effectively reduces NO\textsubscript{x} when employed outside of the optimum primary excess air ratio range, i.e., excess air ratios higher than 1 and less than 0.9. The experiments with FGR located above the grate exhibit higher reduction potential, while FGR located below the grate produces decreased reduction. The recycled-NO conversion factor, which gives a measure of maximal FGR efficiency, at the maximum point, is nearly 100% when FGR is applied below the grate and is 85%–100% in the case of recirculation above the grate.

INTRODUCTION

According to recent findings, the CO\textsubscript{2} concentration in the atmosphere should not be higher than 350 ppm.1 This limit was surpassed in 1988 and measurements taken in November 2011 found a CO\textsubscript{2} concentration of 390 ppm.2 Biomass can provide an easily accessible source of renewable energy that is almost CO\textsubscript{2}-neutral.

Almost all types of biomass contain nitrogen-bound compounds, which makes thermal conversion a challenge, with regard to NO\textsubscript{x} formation. Typical nitrogen contents vary from below 0.1 wt % in wood to 7 wt % in sewage sludge. Demolition wood, which is the fuel used in this study, is an inexpensive source of fuel that is even more challenging to combust, because of its relatively high nitrogen content, which results in high NO\textsubscript{x} emissions. NO\textsubscript{x} contributes to environmental problems such as acid rain, smog formation, and ozone depletion. Therefore, many countries enforce strict regulations on NO\textsubscript{x} emissions from power plants and other combustion systems.

NO\textsubscript{x} Reduction. There are numerous well-established methods that can be applied to reduce the nitrogen oxides emissions from biomass combustion. These methods are categorized as primary and secondary measures based on the location and time of application inside the reactor. Staged air, staged fuel combustion, and flue gas recirculation (FGR) are the most common primary measures and effectively reduce NO\textsubscript{x} emissions inside the furnace. For a better understanding of the NO\textsubscript{x} formation and reduction, processes such as pyrolysis, tar and char combustion, and connected nitrogen conversion should be considered.3

The staged-air combustion reduction mechanism and the related chemistry have been extensively described elsewhere.4–9 The important species and intermediates for NO\textsubscript{x} formation and reduction are NH\textsubscript{3}, HCN, NO, and HNCO.10–14 Fuel-N Conversion. The reaction mechanism for fuel-N conversion, the main source of NO\textsubscript{x} in biomass combustion, is fairly well understood. The contribution of the fuel NO\textsubscript{x} to the total NO\textsubscript{x} in solid fuel combustion is shown to be greater than 75%–80%, with the rest originating mainly from the thermal NO\textsubscript{x} mechanism.7,15–19 The share of fuel-N to NO\textsubscript{x} is even higher in biomass combustion, in which the reactor temperature is relatively low, compared to that of coal combustion.7 Note that thermal NO\textsubscript{x} formation becomes important at temperatures above 1300–1400 °C, which is generally relevant to, e.g., pulverized fuel combustion. However, in our grate furnace, all experiments are carried out at a constant temperature of 850 °C. We also note that, even in the flame region (primary zone), the temperature is below the range within which thermal NO\textsubscript{x} is formed. The positive effect that temperature exerts on NO decomposition in the fuel-rich primary zone is reduced because of increased NO formation in the secondary stage caused by secondary air addition.19

Biomass, on the other hand, contains considerable amounts of fuel nitrogen, which promotes the formation of fuel NO\textsubscript{x} during combustion. Therefore, it is important to understand that FGR in biomass combustion may not be as effective as it is in the combustion of natural gas or oil. However, it has been
proven that air staging and FGR are effective NOx reduction methods for high-nitrogen-content fuels.20 The nitrogen conversion path includes char and volatiles, and the proportion of each depends on the temperature and fuel type.

The released intermediate NOx species, HCN and NHx, can be converted to NO through oxidation reactions via amines (mostly NH-type radicals) or reduced to N2, depending on the stoichiometric conditions, temperature, residence time, etc.21

The residence time is one of the important parameters in NOx formation/reduction. Up to a certain point, an increased residence time in the primary stage will enhance the NOx reduction potential. In this work, the residence time is well above the expected required time (<2 s),19 thus, the results are not influenced by the residence time. The residence time in the primary zone (90 cm) of the reactor in this study is 13–23 s.

Flue Gas Recirculation (FGR). FGR is most likely one of the oldest NOx reduction measures used in oil and gas combustion. The employment of FGR in grate-fired coal combustion has also exhibited a considerable NOx reduction potential.21 The main advantage of FGR and staged combustion is that they can be applied in existing boilers with low cost and few modifications to the furnace, while the implementation of secondary measures such as selective noncatalytic reduction (SNCR) and especially selective catalytic reduction (SCR) is generally more costly.

NOx reduction through FGR is achieved because:

1. the recirculated flue gas acts as an inert gas containing mainly CO2, H2O, a low level of O2, and N2. When mixed with the combustion air, it lowers the temperature in the flame region and, hence, reduces thermal NOx formation;
2. by mixing the flue gas with the combustion air, the oxygen availability in the reaction zone is reduced, which consequently affects the NOx formation chemistry; and
3. the residence time of the recirculated NOx is increased by allowing it to go through the combustion zone a second time.

The high concentration of CO2 caused by FGR is known to influence the formation of H/O/OH radicals, which play a critical role in NOx emissions.22 In the mentioned study, the concentration of H/O/OH radicals with elevated CO2 concentration is different in the reburning zone and the burnout zone. Generally, in the first stage (i.e., the reburning zone), the higher CO2 content results in reduced radical formation, while the radical formation is increased in the burnout zone. On the other hand, the relative order of the quantity of radicals is H > OH > O in O2/N2 combustion, while in O2/CO2 combustion, it changes to OH > O > H.22 In addition to the effects of FGR on the actual residence time and the radical formation mechanisms, a higher CO2 concentration in the inlet oxidant may enhance char nitrogen conversion.23

The effect of oxygen enrichment has been studied primarily in coal combustion and co-combustion systems.24–28 Recent investigations have also been carried out with O2/CO2 as oxidants rather than oxygen-enriched air.27 This study showed that, in coal combustion, the fuel-N to NO conversion factor decreased as the CO2 concentration increased in the presence of coal. The authors also stated that the interaction of fuel-N with recycled NO caused the conversion ratio to decrease as the NO concentration increased in the recycled gas and that the global conversion factor depends on the excess air ratio; these findings are consistent with the present investigation.

Reburning of recirculated NO from the flue gas has also been studied using propane in a burner to avoid fuel-N and heterogeneity effects.28 Those experiments showed that the reduction potential of reburning is lower in oxy-fuel (high O2 concentration in the inlet oxidant) than in air combustion, and applying FGR to oxy-fuel combustion systems increased the total NO reduction.

Combustion of different types of coal in an electrically heated combustor with recycling ratios of 0.2–0.4 showed a recycled-NO reduction of 60%–80% at equivalence ratios of ~1.4, while the reduction was less at low recycling ratios.29,30 The effects of CO2 concentration, recycled NOx, and interactions between the fuel-N and the recycled NOx on NOx emission have been studied in coal combustion with recycled CO2, and a 50%–80% reduction of recycled NO in the furnace was found.31

Many studies have also been performed in waste combustion plants, because of the higher nitrogen content of waste. Bianchini et al.32 performed a study on a fluidized-bed reactor (FBR) with 60% recirculation of hot flue gas. Their study included temperature effects and showed that FGR can reduce NOx emissions up to 30% in waste-to-energy plants. A NOx reduction of up to 20% was also achieved in a waste incineration plant using an FGR ratio of ~25%.33 Investigations of high-temperature air combustion in the incineration of solid waste also demonstrated that NOx emission was reduced by 28%–38% when FGR was used to decrease the oxygen concentration.34

In this study, a combination of staged-air combustion and flue gas recirculation was applied to a grate-fired laboratory-scale reactor to mitigate NOx emissions. As stated above, these measures have known effects when applied individually. However, staged combustion has a known optimum effect within a rather narrow window of excess air ratios. In the present work, we address how this effect can be modified by including FGR. The experiments performed provide important data for assessing the effect of combined staged-air combustion and FGR on NOx formation in the combustion of demolition wood, a fuel that contains a relatively high nitrogen concentration. The parameters that have been investigated in this study are (1) the amount of recirculated flue gas, (2) the recirculated flue gas composition, and (3) the point of flue gas introduction inside the reactor.

## EXPERIMENTAL SETUP AND PROCEDURE

### The Multifuel Reactor

The SINTEF Energy Research’s grate-fired laboratory-scale multifuel reactor was used to carry out the combustion tests. This reactor is an electrically heated high-temperature reactor. Figure 1 shows a schematic drawing of the reactor. The reactor has a ceramic inner tube with a diameter of 100 mm and a length of 2 m. The vertical tube consists of two ceramic tubes 1 m in length connected by a ceramic socket. The ceramic tubes are made of nonporous and noncatalytic alumina. A more-detailed description of the reactor can be found in a recent study by Khalil et al.35 The reaction section, located above the grate, is 1.6 m long, while the section below the grate is 0.4 m long. The reactor is fitted with a unique two-level grate system, as shown in Figure 2, which allows for two-stage fuel burning. Its function will be described in more detail in the next section. As shown in the photo, the blades are designed to keep the pellets on both grates (upper and lower level) for the same amount of time, i.e., the blades rotate at the same speed at both grates. The heating system fits inside the insulation shell and consists of four separate heating zones.

Figure 3 shows the sampling lines for gas concentration measurements. The gas concentration in the primary stage (NO, HCN, NHx...) is measured by a Fourier transform infrared (FTIR)
The fuel pellets are fed automatically from a fuel container located above a water-cooled piston. The piston transports the fuel into the reactor, and the pellets fall down on the upper grate, after which the piston quickly returns to its starting position and the process is repeated. The feeding frequency was set to ~6–7 s, which produced a feeding rate of ~400 g/h. The piston frequency was carefully calibrated prior to each experiment.

The pellets were primarily combusted on the upper (primary) grate. The pellets were then gradually moved to a slot leading to the second (final burnout) grate by means of rotating blades. Each grate has two blades rotating slowly, which complete a circle within ~3 min. Final burnout takes place on the lower grate before the ash is moved to the ash bin through another rotating blade. The gas residence time between the grate levels is in the range of 1–2 s, and the total residence time of the fuel gases in the reactor is ~25–50 s, because of a low flow velocity.

As mentioned earlier and shown in Figure 3, two FTIRs were used in this experimental work. The challenge with the one located just above the grate is to measure the intermediate nitrogen species present as minor compounds in a gas stream containing a wide variety of compounds that vary substantially in time. This system is difficult to measure using an automated method and must be checked manually. The sample line for this FTIR was cooled to remove all compounds that vary substantially in time. This system is difficult to measure using an automated method and must be checked manually. The sample line for this FTIR was cooled to remove all compounds that vary substantially in time.

**Experimental Procedures.** The experimental matrix is presented in Table 1. The experiments were carried out using 6-mm-diameter pellets of demolition wood and in two modes: (1) experiments using FGR in the primary zone, and (2) experiments using FGR in the secondary zone. Recirculated flue gas was either mixed with primary air and fed to the reactor ca. 30 cm below the grate, or mixed with secondary air before being fed to the reactor ca. 90 cm above the grate. These two FGR modes are used to obtain more information about the NO\textsubscript{x} emission levels and the reduction potential of FGR, as each mode results in different chemistry inside of the reactor. The obtained results can be used as a basis for improved design and operation of larger scale combustion systems. Most of the available studies on FGR used CO\textsubscript{2} as the recirculated flue gas. However, we also included nitrogen oxide in the flow, similar to how FGR is used in an industrial boiler. Each case was carried out with two different recirculated flue gases: CO\textsubscript{2} only and CO\textsubscript{2} + NO. Only isothermal experiments were performed, and the reactor temperature was 850 °C. Experiment 5 is considered to be the reference experiment and is performed only with air (i.e., without any flue gas recirculation). The total excess air ratio was ~1.6, and the primary excess air ratio was ~0.8. The excess air ratio (λ) is defined as the ratio between the air-to-fuel ratio at the measurement time (A/F) and the stoichiometric air-to-fuel ratio ((A/F)\textsubscript{stoic}). Hence, λ \textless 1 indicates fuel-rich conditions. The stoichiometric condition is defined using the fuel composition (ultimate analysis).

The proximate and ultimate analyses are shown in Table 2. The demolition wood (DW) has a relatively high nitrogen content of 1.06 wt %, and DW can be regarded as a relatively safe fuel, in terms of Cl-related corrosion issues, compared to, e.g., agricultural residues or waste. The ash content of DW is higher than that of virgin wood and requires an ash collection and disposal system for proper handling in a combustion plant.

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generated by mixing a calibration gas containing NO (in N₂) with N₂ purity of 5.0. The NO content was calibrated within the range of 0−350 ppm and the two methods yielded NO concentrations that were within 5% of each other. The data from the PLS model was used for the calculations shown in this work. The challenge, however, was to develop a method for measuring the HCN content. HCN in the FTIR spectrum is present in the narrow wavelength range of 3400−3200 cm⁻¹. This range also absorbs C₂H₂ and H₂O, and no single peak can be used to measure the HCN content. A PLS model was developed for HCN prediction in the range of 3382−3350 cm⁻¹, which also included corrections for the above-mentioned compounds. The HCN content was calibrated using spectra with concentrations between 0 and 350 ppm. The quality of the model was checked by measuring the height of a single peak after the interference spectra of C₂H₂ and H₂O were subtracted. To do so, the concentrations of these interfering compounds were predicted prior to the HCN content. The subtraction was performed using a function in the software that was provided with the FTIR analysis. This process is time-consuming and was only performed on selected spectra to ensure that the PLS model was performing satisfactorily. The difference between the two methods was similar in magnitude to the difference in the NO predictions.

The experiments were carried out using the following parametric variations:

(1) CO₂ recirculation at different concentrations, relative to the combustion air;
(2) CO₂/NO recirculation at different concentrations, relative to the combustion air; and
(3) for each of the above methods, two recirculation locations were investigated: below the grate and ∼90 cm above the grate.

Table 1. The Experimental Matrix

<table>
<thead>
<tr>
<th>FGR location</th>
<th>CO₂ (vol % of total air flow)</th>
<th>NO (ppm in total air flow)</th>
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</thead>
<tbody>
<tr>
<td>1 primary zone</td>
<td>2.4</td>
<td>17</td>
</tr>
<tr>
<td>2 primary zone</td>
<td>3.3</td>
<td>28</td>
</tr>
<tr>
<td>3 primary zone</td>
<td>5.9</td>
<td>41</td>
</tr>
<tr>
<td>4 primary zone</td>
<td>6.7</td>
<td>47</td>
</tr>
<tr>
<td>5 reference experiment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 secondary zone</td>
<td>2.5</td>
<td>17</td>
</tr>
<tr>
<td>7 secondary zone</td>
<td>4.6</td>
<td>19</td>
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<tr>
<td>8 secondary zone</td>
<td>6.4</td>
<td>47</td>
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<tr>
<td>14 secondary zone</td>
<td>4.4</td>
<td>47</td>
</tr>
<tr>
<td>15 secondary zone</td>
<td>4.5</td>
<td>64</td>
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</table>

Table 2. Fuel Proximate and Ultimate Analysis

<table>
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<tr>
<th>Pellet</th>
<th>Proximate Analysis (wt % on dry basis)</th>
<th>Ultimate Analysis (wt % on dry ash-free basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ash</td>
<td>volatile matter</td>
</tr>
<tr>
<td>demolition wood, DW</td>
<td>2.18</td>
<td>75.97</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

In this section, the observed results from the experiments are presented.

As mentioned earlier, NOₓ precursors in the primary zone (above the top grate) were detected and quantified using FTIR spectroscopy. In all of the experiments, the concentration of ammonia (NH₃) was below the detectable limit. It seems that the conditions under which these experiments were performed favored the formation or survival of HCN and NO in the region where the samples were taken for analysis. In addition, the FTIR analyzer used a suction probe located 25 cm above the grate. This distance corresponds to several seconds of residence time above the fuel pellets, which is more than enough time for NH₃ to be fully converted to other intermediate N-species, including HCN, or N₂,36,37 while further reactions are limited by the very low remnant radical pool. When secondary air is added, some further reduction of the remaining intermediate N-species to N₂ will occur, while the remainder will be converted primarily to NO.

CO₂ Recirculation. Figure 4 shows NOₓ emission levels in the flue gas at different excess air ratios for all of the experiments performed with recirculation of CO₂ alone. The maximum NOₓ emissions for the different experiments were in the range of 90−115 ppm (11 vol % O₂ in dry flue gas) for low excess air ratios (ca. 0.7) and were reduced to as low as 30 ppm for an excess air ratio close to 1. The right graph demonstrates that the addition of CO₂ has a positive effect on NOₓ reduction.
above the grate. The left graph presents the same trend below the grate but with more widely scattered data points. The reverse effect is observed in the case of 3.3% CO2, which could originate from the combustion instabilities in the mentioned experiment. Because of the desired reduction chemistry in the first stage, the primary air should be supplied to the reactor to create reducing conditions and thus maximize NOx reduction. Compared to the reference experiment, in which no CO2 recirculation was employed, the NOx concentration was more strongly reduced at increased amounts of CO2 recirculation. However, it should be noted that the reduction due to FGR is much lower than that of air staging. The total reduction at the optimal condition is ~70%, while CO2 recirculation provides an additional reduction of 5%–10%, depending on the amount of recirculated CO2. The CO2 addition lowers the local temperature (electrically heated reactor) due to the increased heat capacity of the flue gas and lowers the O2 concentration inside the reactor, which, in return, decreases the formation of nitrogen oxides. A long residence time in the primary (reduction) zone ensures a low NOx emission level at the
optimum primary excess air ratio, i.e., a very high reduction level. Therefore, the additional effect of the second method, FGR, is minimal at the optimum primary excess air ratio, as explained in the Introduction section.

The FGR position also has a clear effect on the NO\textsubscript{x} emissions. The left graph in Figure 4 shows that the additional CO\textsubscript{2} in the primary zone (i.e., below the grate) contributes to NO\textsubscript{x} reduction over a wide range of excess air ratios. However, at the optimum excess air ratio, the effect of FGR is minimal. The widely scattered results in this graph may be due to unstable combustion conditions, while FGR above the grate keeps the combustion quite stable. The right graph presents the same results with CO\textsubscript{2} recirculated above the grate, and the reduction level is clearly visible and higher even at the optimum primary excess air ratio. For instance, at a low primary excess air ratio of ca. 0.7, the maximum NO\textsubscript{x} emission level at the highest FGR ratio is reduced by \(~\sim\)20\% from the reference experiment in the case of FGR above the grate. Under the same conditions, FGR below the grate reduces the NO\textsubscript{x} emission level by 25\%.

The CO\textsubscript{2} concentration in the flue gas can be calculated as follows:

\[\text{CO}_2 + \text{NO} \text{ under the grate} \]

\[\text{CO}_2 + \text{NO} \text{ above the grate} \]

**Figure 6.** Effects of the primary excess air ratio and amounts of CO\textsubscript{2} and NO in the inlet oxidant on the NO\textsubscript{x} emissions: (left) CO\textsubscript{2} + NO below the grate and (right) CO\textsubscript{2} + NO above the grate.

**Figure 7.** Effects of CO\textsubscript{2}/NO in the inlet oxidant on the NO and HCN levels in the primary zone: (left) CO\textsubscript{2} + NO below the grate and (right) CO\textsubscript{2} + NO above the grate.
where $\alpha$ is the CO$_2$ concentration in the flue gas, $\beta$ the inlet CO$_2$ concentration, and $\gamma$ the FGR ratio.

The gas concentration measurement in the primary zone which is carried out using FTIR spectroscopy, reveals the effects of different CO$_2$ recirculation levels on the formation of NO$_x$ precursors. Figure 5 shows the minimum, maximum, and average concentrations of HCN (in ppm) in the upper graphs. The HCN content exhibits a weak tendency to decrease with increasing CO$_2$ recirculation at the injection point above the grate, with the exception of the points 2.5% to 4.7% above the grate. Further studies using more FGR ratios (CO$_2$ levels) between 2.5 and 5.0% are required to clarify this issue. Please note that max and min values do not correspond to uncertainties; instead, these are the measured maximum and minimum values at the different excess air ratios tested for each experiment. The difference between the average NO levels at different FGR ratios and CO$_2$ injection points compared to the reference experiment is minimal. The measured concentration of NO in the primary zone above the grate is presented in the lower graphs of Figure 5. In this case, the decreasing tendency of the NO concentration with increasing CO$_2$ is clearly visible up to a certain CO$_2$ percentage. For the experiments with CO$_2$ injection above the grate, the NO concentration decreases as the CO$_2$ recirculation increases up to 6.5%. However, the NO concentration in the recirculation gas did not continue to decrease once the CO$_2$ concentration increased above 2.5% CO$_2$. More investigations are required in future work to clarify this behavior.

**CO$_2$ + NO Recirculation.** The effect of the primary excess air ratio and the amount of NO recirculation is shown in Figure 6. The left graph presents the NO$_x$ emission in the flue gas for the experiments applying FGR below the grate. In this case, the NO$_x$ emission levels are very similar to those presented above, which demonstrates that the NO$_x$ emission levels are unaffected by the increased NO concentration in the recirculated gas. This finding indicates that the NO that is returned to the reactor undergoes complete conversion. The elementary reactions that reduce the NO introduced into the reactor are heterogeneous reactions with char on the bed or homogeneous reactions with volatiles in the gas phase. The corresponding reactions are suggested to be the direct conversion of NO to N$_2$ through NO $\Leftrightarrow$ N$_2$, and NO $\Leftrightarrow$ N$_2$O, including the elementary reaction N$_2$O + (CO) $\Leftrightarrow$ N$_2$ + CO$_2$. The right graph shows the same scenario with FGR located above the grate. In this case, the NO$_x$ emission levels in the flue gas increase as the NO concentration in the recirculated gas increases. The data in the right graph demonstrate the existence of a distinct minimum in the NO$_x$ emission levels within a primary excess air ratio range of 0.9–1 for all cases. This holds true even though the optimal minimum differs as a function of the CO$_2$/NO concentration in the recirculated gas. The mentioned excess air ratio has been shown to be optimal in several experimental campaigns performed on different fuels and under different operating conditions. These results show that the excess air ratio that achieves the optimum NO$_x$ reduction for the reactor design used in the current study is ~0.9–0.95. This finding is in agreement with the modeling and kinetics studies on NO$_x$ reduction by fuel or air staging, which also find that the optimal excess air ratio is close to 1.9,40

Figure 7 presents the HCN and NO concentrations above the grate, close to the devolatilization zone. The experimental data suggest that the average HCN concentration above the grate increases as the NO concentration in the recirculated flue gas increases when the FGR is located below the grate. This trend may be due to the higher level of available fixed nitrogen and increased conversion of char nitrogen. However, the HCN concentration does not exhibit a clear dependency on the FGR ratio when FGR is located above the grate. The average NO concentration also does not exhibit a clear trend. It is also important to note that the maximum NO values decrease as the NO concentration in the inlet flow increases (Figure 7, right graph). This result can explain the higher HCN concentration in the corresponding cases.

The HCN and NO concentrations in the primary zone for the experiments employing FGR in the secondary zone are presented in the bottom graphs of Figure 7. The average HCN and NO concentrations (150–175 ppm and 160–195 ppm, respectively) are quite constant. With FGR located in the secondary zone (above the grate), the possible effects of the recirculated CO$_2$ and NO on char-N conversion are avoided. In addition, the volatile N-species very near the fuel bed and just above the pellets are unaffected by the FGR, gases because the secondary air feeding point is placed at a somewhat higher position. Therefore, there is no interaction between the fuel bed and the recycled flue gas, and the reaction mechanism at the bed does not change compared to the reference case, which leads to the relatively constant concentrations of intermediate species in this case.

To characterize the effect of FGR on NO$_x$ emissions, a new parameter is introduced: the recycled-NO conversion factor ($\eta_{NO}$). Figure 8 shows the influence of FGR on the recycled-NO reduction for experiments run with FGR located below the grate (top graph) and above the grate (bottom graph). The recycled-NO conversion factor is defined based on the NO$_x$ emission level, consisting of mainly NO$_x$ in the flue gas compared to that of the reference experiment where only staged air combustion is applied to the reactor. Therefore, this quantity provides a measure of FGR effectiveness; a NO conversion factor of 1 corresponds to maximum reduction of the recycled NO.

$$\eta_{NO} = \frac{NO_{ppm \text{ in inlet gas}} - (NO_{in,NO + CO_2 case} - NO_{in, CO_2 case})}{NO_{ppm \text{ in inlet air}}}$$

The upper graph indicates that when FGR is located in the primary zone, all of the recirculated NO can be converted to N$_2$. The maximum values shown in Figure 8 indicate 100% NO reduction is achieved in all experiments with FGR below the grate. The average values also indicate a considerable NO$_x$ reduction of 60%–100%. The lower graph presents the same results with FGR located above the grate, with a maximum NO$_x$ reduction of 85%–100% and an average reduction of 54%–66%. The reduction potential is higher with FGR located below the grate than above the grate, because of the lower residence time of the inlet NO under reducing conditions when it is supplied to the reactor in the secondary zone, in addition to the different heterogeneous kinetics available for NO and char nitrogen conversion.
In this study, experiments on combustion of demolition wood are performed in a laboratory-scale reactor. The most important findings were the following:

- The optimum air distribution that maximized the NO reduction level was a primary excess air ratio of 0.9–1 for all experiments, regardless of the flue gas recirculation (FGR) ratio and the NO concentration in the inlet gas.
- The NO reduction level from staged air combustion at the optimum primary excess air ratio was ∼70%.
- Applying FGR to the reactor allows NO reduction to be reduced by ∼75%–80% under the optimum combustion condition, i.e., 5%–10% more than the reduction without FGR.
- The results show that the NO reduction level depends heavily on the stoichiometric conditions in the primary (reduction) zone. The effectiveness of FGR is higher outside of the optimum range of excess air ratios.
- The experiments employing FGR in the secondary zone exhibit higher reduction potential, while FGR in the primary zone gives lower reduction. The recycled NO-conversion factor at the maximum point is almost 100% for FGR below the grate and 85%–100% for FGR above the grate.

**CONCLUSIONS**

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**Notes**

The authors declare no competing financial interest.

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