EXPERIMENTAL VERIFICATION OF THE EFFICIENCY OF SELECTIVE NON-CATALYTIC REDUCTION IN A BUBBLING FLUIDIZED BED COMBUSTOR

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ABSTRACT. Controlling nitrogen oxide (NO\textsubscript{X}) emissions is still a challenge as increasingly stringent emission limits are introduced. Strict regulations will lead to the need to introduce secondary measures even for boilers with bubbling fluidized bed (BFB), which are generally characterized by low NO\textsubscript{X} emissions. Selective non-catalytic reduction has lower investment costs compared to other secondary measures for NO\textsubscript{X} reduction, but the temperatures for its efficient utilization are difficult to achieve in BFBs. This paper studies the possibility of an effective application of selective non-catalytic reduction (SNCR) of nitrogen oxides in a pilot-scale facility with a bubbling fluidized bed. The effect of temperatures between 880 and 950°C in the reagent injection zone on NO\textsubscript{X} reduction was investigated. For the selected temperature, the effect of the amount of injected reagent, urea solution with concentration 32.5% wt., was studied. The experiments were carried out using 500 kW\textsubscript{th} pilot scale BFB unit combusting lignite. In addition, an experiment was performed with the combustion of wooden pellets. With reagent injection, all experiments led to the reduction of nitrogen oxides and the highest NO\textsubscript{X} reduction of 58% was achieved.

KEYWORDS: Selective non-catalytic reduction, SNCR, fluidized bed, BFB, denitrification.

1. INTRODUCTION

The future of the energy industry is inextricably linked to the need to prevent the release of pollutants and greenhouse gases. One of the monitored pollutants is nitrogen oxides, which is the collective term for nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). Their formation is well known and is described even in fluidized bed combustion [1,2]. Nitrogen oxides have a negative impact on the environment and contribute to problems such as acid rain, ozone depletion, and photochemical smog [3]. The nitrous oxide (N\textsubscript{2}O) is a gas with a greenhouse effect. It is also formed during combustion, particularly at lower temperatures. At higher temperatures (greater than 1500 K), it is rapidly decomposed, forming N\textsubscript{2} or NO [4]. Therefore, its emissions may be of significance in the case of combustion in fluidized beds, which are generally operated at lower temperatures and do not reach the temperature range for its oxidation. Besides the combustion process itself, its significant source can be an application of a selective non-catalytic reduction of NO\textsubscript{X} [5], particularly at elevated ratios of the reducing agent [6].

Fluidized bed boilers are widely used for their advantages, such as fuel flexibility, uniform temperature distribution, and operation at low temperatures. Bubbling fluidized bed (BFBs) as well as circulation fluidized bed combustors (CFBs) allow the combustion of fuels of different sizes, moisture content, and heating values, and therefore can be used not only for the combustion of coal, but also for the combustion of biomass or various alternative fuels. The operating temperatures in the fluidized bed are in the range of 800–950°C [2]. This lower operating temperature range also leads to a lower formation of NO\textsubscript{X}. The formation of nitrogen oxides can generally be realised by three mechanisms – thermal, prompt, and fuel NO\textsubscript{X} [3,9]. The thermal and prompt pathways become more important above the operating temperature range of fluidized bed combustors and are therefore negligible during fluidized bed combustion and fuel NO\textsubscript{X} is then considered the main contributor to nitrogen oxides.

2. MEASURES FOR NO\textsubscript{X} REDUCTION

Reduction of NO\textsubscript{X} emissions can be achieved by modifying the combustion process, thereby preventing the formation of NO\textsubscript{X}, known as primary measures, or by secondary measures, which are techniques for the reduction of already generated nitrogen oxides.

In principle, all primary measures involve adjustments leading to combustion conditions with a decreased O\textsubscript{2} availability at the early stage of the combustion process, a reduction of the maximum flame temperature, or a change in residence time in different parts of the combustion zone [5]. For fluidized bed combustors, the early stage of the combustion process takes place in the dense bed zone. One of
the measures can be air staging, which presents the oxygen-lean primary combustion zone and the oxygen-rich secondary combustion zone. It is realized by supplying secondary or even multi-stage air above the area of primary combustion, typically to the freeboard of the BFBs or to the lean bed zone of the CFBs. Air staging is often used in BFBs to control combustion and ensure the required temperature and overall oxygen stoichiometry. The use of flue gas recirculation is required for fluidized bed combustion because it provides the necessary volume flow to fluidize the bed material. Most primary measures are less effective in the case where the generated NO\textsubscript{X} is predominantly formed by the oxidation of fuel nitrogen \[5\], which is a typical situation for fluidized bed combustors. Therefore, to meet the NO\textsubscript{X} limits, secondary measures may be necessary.

Secondary measures are used to reduce nitrogen oxides that have been already formed. These post-combustion technologies that reduce NO\textsubscript{X} are mainly selective catalytic (SCR) and selective non-catalytic reduction (SNCR). These flue gas treatments reduce NO\textsubscript{X} to N\textsubscript{2} by reaction with an amine-based reagent, such as ammonia or urea. Both technologies are widely used.

In the process of SCR, the catalyst is present, reducing the activation energy of key reactions. Therefore, the reduction of NO to molecular nitrogen is realized in the temperature range 290–450 °C \[10\]. The efficiency of SCR at similar reducing agent stoichiometric ratio is higher than for SNCR and can reach above 90%, however, the investment and operating costs are significant and its installation has a large space requirement \[11\]. This may limit its application as a retrofit to an existing facility. Additional problems can be fouling and catalyst poison. On the other hand, SNCR can be easily retrofitted, and its investment costs are lower because of the absence of the catalyst.

2.1. SELECTIVE NON-CATALYTIC REDUCTION

SNCR is a well-known and described technology \[5\], but its application in fluidized bed combustors is rare. This is mainly due to the lower formation of NO\textsubscript{X} in fluidized bed combustion, which can then operate within the emission limits. The problem may arise if these limits for NO\textsubscript{X} emissions are even stricter or fuels with higher fuel-nitrogen content are burned, for example, non-wooden biofuels.

Several different reducing agents can be used in the SNCR process. The reduction process with ammonia is called the Thermal DeNOx process, whereas the use of urea is called the NOxOUT process. A less common reducing agent is cyanuric acid within the RAPRENOx process. Since urea decomposes into ammonia and cyanuric acid, the SNCR process with urea can be considered as the combination of the other two \[12\]. The reaction path of urea within the selective non-catalytic reduction is shown in Figure 1, which describes the decomposition of urea into ammonia and cyanuric acid and subsequent reactions.

The reduction of NO\textsubscript{X} occurs in a temperature range called a temperature window. This required temperature window is affected by many factors and the influence on it has parameters such as the reducing agent, the composition of the flue gas, the residence time, and the mixing between the reagent and the flue gas \[5\]. However, the interval is usually given in the range 800–1 100 °C; the temperature window for ammonia is 850–1 000 °C and for urea is the temperature window wider (800–1 100 °C) \[13\]. Below these temperatures, the reaction is too slow and most of the injected ammonia remains unreacted, increasing the slip of ammonia. At temperatures above 1 200 °C, the degree of NO\textsubscript{X} reduction decreases due to the thermal decomposition of the reagent that subsequently oxidizes \[5\].

![Figure 1. Reaction path diagram with urea as a reagent](image-url)
The amount of reagent injected is usually represented by a normalized stoichiometric ratio (NSR), which defines the number of moles of injected NH$_2$ reagent relative to the number of moles of NO$_X$. For SNCR, the preferred normalized stoichiometric ratio is greater than 1, and a ratio NSR in the range of 1.5–2.5 is generally recommended [13].

As mentioned above, the temperatures in the dense bed of BFB are usually in the range 800 – 900 °C, and therefore it is evident that it is difficult to reach sufficiently high temperatures in the freeboard zone for efficient SNCR application. However, our previous work [14] that has been done in a laboratory-scale BFB combustor confirmed that such temperatures can be reached in the freeboard section of a BFB combustor through an intensively staged supply of combustion air. Such an intensive air staging, which means that understoichiometric conditions are established in the primary combustion zone in the dense bed, is not typically applied in the industrial practice. In parallel, the application of SNCR in a BFB combustor is not common, and the original experimental data from this study contribute to the possible realization of this technology.

In this article we have therefore focused on an experimental study of real performance of the selective non-catalytic reduction of NO$_X$ in a 500 kW$_{th}$ pilot scale BFB combustor in connection with intensive air staging in order to increase the temperature of gas phase in the freeboard section, where the reducing agent was injected. This temperature was in the range for effective reduction of NO$_X$. In this work, the characterization of the SNCR performance in correlation with the NSR and the temperature in the freeboard section where the reducing agent was injected is presented.

3. EXPERIMENTS
3.1. EXPERIMENTAL SETUP

The experiments were carried out in a pilot scale bubbling fluidized bed combustor with a thermal input of 500 kW, and its scheme is given in Figure 2. The facility is very variable as it allows combustion of different fuels with different oxidants; it is possible to use oxygen-enriched air up to the pure oxy-fuel regime. In the case of the air regime, a mixture of primary air and recirculated flue gas provides the fluidization, and its volume and mixture ratio can be changed arbitrarily. The combustion chamber together with the freeboard is insulated with fireclay lining, and the walls of the boiler are water-cooled. Four secondary air distributors are evenly spaced around the perimeter and each can supply secondary air at 4 heights. In addition, the inspection windows are located in the freeboard, which can be used for injection of reagent within the selective non-catalytic reduction process. The flue gas was continuously sampled. The volumetric fraction of O$_2$ was measured using a paramagnetic sensor and using a lambda probe (for operation). The volumetric fractions of SO$_2$, CO$_2$, CO, NO$_X$ (sum of NO and NO$_2$), and N$_2$O were measured using NDIR sensors. The volumetric fraction of NH$_3$ was measured using a FTIR analyzer.

For selective non-catalytic reduction, the main part of realization is reagent injection. In this case, a single probe with a spray nozzle was used (Figure 3). The probe is water-cooled, and compressed air is used to atomize the reagent. The probe can be placed at five different heights along the freeboard zone using inspection windows. The reducing agent was transported from an accumulation vessel to the nozzle by increasing the air pressure above the level of the reducing agent in the accumulation vessel. The volumetric flow of the reducing agent was controlled by a manually operated proportional valve placed in the stream of the reducing agent. Two rotameters were used to measure the volumetric flow of the reducing agent, which
As received Dry ash free

<table>
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<th>Water [wt. %]</th>
<th>Ash [wt. %]</th>
<th>Comb. [wt. %]</th>
<th>C [wt. %]</th>
<th>H [wt. %]</th>
<th>N [wt. %]</th>
<th>S [wt. %]</th>
<th>O¹ [wt. %]</th>
<th>Volatiles [wt. %]</th>
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<td>1.1</td>
<td>1.3</td>
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</tr>
<tr>
<td>Wood</td>
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<td>7.8</td>
<td>1.5</td>
<td>90.7</td>
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<td>6.9</td>
<td>0.3</td>
<td>0.003</td>
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</table>

¹ Calculated as balance to 100 %.

Table 1. Proximate and ultimate analysis of the fuels used within the experiments.

The experiments were carried out using Czech lignite Bílina HP1 135 and wooden pellets as fuels. The proximate and ultimate analyses of the lignite and wooden pellets are given in Table 1.

During experiments with lignite coal, its inherent ash was used as a bed material. Experiments with biomass were realized combusting wooden pellets (according to the standard ENplus A1) and using a lightweight ceramic aggregate with a mean diameter of 1.12 mm as a bed material, which is described in detail in [7].

The reagent used in all experiments with lignite as fuel was a urea solution with a concentration of 32.5 % by weight. Since the wooden biomass combustion is expected to lead to a lower production of NOX due to the significantly lower nitrogen content in the fuel, it was necessary to adjust the concentration of reagent to 10.8 % wt. to ensure sufficient flow of the urea solution.

Several series of experiments were performed for lignite and one experiment for the combustion of wooden pellets. In order to achieve temperatures in the freeboard zone (where the injection takes place) suitable for effective nitrogen oxides reduction using SNCR, the high level of staged supply of combustion air had to be realized. The stoichiometry in the fluidized bed for individual experiments is given in Table 2 for lignite combustion. In the case of combusting wooden pellets, the operating range differed in the operating range - the first measured flow in the range 0–1.21 l/h and the second in the range 1–5 l/h.

To achieve the temperature window for efficient injection of the reagent, air staging was realized. It leads to the primary zone with sub-stoichiometric conditions, above which the secondary air inlet is located that creates fuel-lean zone. Thanks to this measure, it was possible to obtain higher temperatures in the freeboard area while keeping the bed temperature below 900 °C. Air staging simultaneously serves as a primary measure that leads to a reduction of NOX.

A comparison of temperature profiles within the combustor during non-staged and staged combustion is given in Figure 4. The dashed horizontal line indicates the height level of secondary air supply in the combustor. Each point in the chart corresponds to a mean temperature value measured at that specific position. The locations of the thermocouples are indicated in Figure 2 by a ‘T’ sign. The height of 0 mm corresponds to the average temperature in the dense bed measured by 4 thermocouples. The temperatures in the freeboard section were measured by two thermocouples at each height. It can be seen that the temperature of the flue gas slightly higher than 950 °C was reached at a height of 1200 mm above the dense bed. At this point, the reducing agent for SNCR was injected.

3.2. Materials and methods

The experiments were carried out using Czech lignite Bílina HP1 135 and wooden pellets as fuels. The proximate and ultimate analyses of the lignite and wooden pellets are given in Table 1.

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pellets, no secondary air was used and the air excess in the dense bed was 1.7. The value representing the freeboard temperature in Figure 2 is an average of values measured at the place of injection of the reducing agent sampled for at least 30 minutes in the interval of 1 s. The average value is given together with the interval of 95% confidence.

The experiments were performed with a constant bed temperature of 880 °C and the oxygen level in the dry flue gas maintained at 6% to diminish the impact of these parameters on the NOX formation. Secondary air was injected 900 mm above the surface of the fluidized bed for lignite. A reference case was measured for each selected temperature and the measured values of the concentration of NOX were used to calculate the corresponding values of NSR and the efficiency of NOX reduction. During all experiments, the selected temperature in the freeboard area was kept constant and the amount of urea solution injected was increased in steps. In the case of lignite combustion, the volumetric flow of the urea solution was increased by 0.251/h, except for the measurement with the freeboard temperature 870 °C, when the step was 0.151/h. Consequently, steady-state cases with volumetric flows of the urea solution of 0, 0.25, 0.5, 0.75, 1, and 1.21/h were measured for freeboard temperatures 882, 885, 925, and 949 °C. For freeboard temperature of 870 °C, volumetric flows of the urea solution were 0, 0.15, 0.3, 0.45, 0.60, and 1.21/h. In the case of biomass combustion, steady states were measured with volumetric flows of the urea solution of 0, 0.4, 0.85, 1.3, 2, and 31/h. The volumetric flow of the urea solution was used together with the reference concentration of NOX to determine the stoichiometric ratio NSR. In the case of urea (NH3)2CO, the normalized stoichiometric ratio is defined as two moles of urea in the urea solution to the mole of NO in the flue gas [15]:

\[
NSR = 2 \frac{n_{\text{urea}}}{n_{\text{NO}}} \quad (1)
\]

The NSR ratio was used in the evaluation of the result as the variable parameter that describes the intensity of the SNCR process. Each of the steady-state cases was measured in the average for 40 minutes (at least for 30 minutes). All measured values were sampled with an interval of 1 s except for the NH3 concentrations and the NOX concentrations measured downstream of the SNCR in the case of lignite combustion and freeboard temperature 920 °C, where the data were sampled with an interval of 1 minute. All sampled data reported in the results are expressed using averages with corresponding intervals of 95% confidence.

4. RESULTS AND DISCUSSION

The measured data from all experiments relevant for this study can be found in Table 3 (for the combustion of lignite) and Table 4 (for the combustion of biomass). All concentrations reported in these tables are calculated for a reference content of O2 in dry flue gas of 6%.

Achieving different temperatures in the freeboard zone was realized by different mass flow of fuel, modification of the volume of fluidizing gas and its composition, and changing the volumetric flow of secondary air as well. These adjustments resulted in different initial concentrations of NOX, which varied from 438 to 498 mg/m3 for lignite combustion. The difference in the initial NOX concentration could also be caused by a slightly different O2 volumetric fraction in the flue gas. The formation of NOX is significantly dependent on the availability of O2 for the oxidation of the fuel N, which was confirmed by Krzywański et al. [16] or Vodička et al. [17]. Although a constant volumetric fraction of O2 in dry flue gas was desired within all experimental cases, its value varied in the range from 4.3 to 7.3%. It can be seen in Table 3 that the higher concentrations of NOX were measured for higher volumetric fractions of O2 and vice versa. The NOX concentrations measured for wood combustion were significantly lower than those measured for lignite combustion, particularly due to the significantly lower nitrogen content in the fuel [15].

The measurement of CO concentration in the freeboard and of NH3 concentration in the flue gas re-

\[
\begin{tabular}{c|c|c}
Freeboard temperature & Required freeboard temperature & Air excess ratio in the dense bed \\
[\text{°C}] & [\text{°C}] & [-] \\
\hline
\text{Combustion of lignite} & \\
870 ± 0.8 & 870 & 0.50 \\
882 ± 0.8 & 880 & 0.94 \\
885 ± 0.8 & 890 & 0.97 \\
925 ± 2.0 & 920 & 0.63 \\
949 ± 0.6 & 950 & 0.53 \\
\hline
\text{Combustion of wood} & \\
886 ± 0.3 & 880 & 1.46 \\
\end{tabular}
\]

Table 2. Stoichiometry in the fluidized bed.
The value was not available for this experiment.

Table 3. Operating conditions during experiments for lignite combustion, $O_{2, ref} \approx 6\%$.

<table>
<thead>
<tr>
<th>Freeboard temp. (required) [°C]</th>
<th>NOX before SNCR [mg/m³]</th>
<th>NOX after SNCR [mg/m³]</th>
<th>$NSR$</th>
<th>$\eta_{NOX}$ [%]</th>
<th>NH₃ [mg/m³]</th>
<th>$O_2$ [mg/m³]</th>
<th>CO [mg/m³]</th>
<th>CO freeboard [mg/m³]</th>
<th>$N_2O$ [mg/m³]</th>
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<td>773±34.9</td>
<td>660±72.5</td>
<td>1883±94.1</td>
<td>660±72.5</td>
<td>1274±39.4</td>
<td>1564±71.6</td>
<td>1564±71.6</td>
<td>1564±71.6</td>
<td>230±0.6</td>
</tr>
</tbody>
</table>

* The value was not available for this experiment.

Table 4. Operating conditions during experiments for biomass combustion, $O_{2, ref} \approx 6\%$.

<table>
<thead>
<tr>
<th>Freeboard temp. (required) [°C]</th>
<th>NOX before SNCR [mg/m³]</th>
<th>NOX after SNCR [mg/m³]</th>
<th>$NSR$</th>
<th>$\eta_{NOX}$ [%]</th>
<th>NH₃ [mg/m³]</th>
<th>$O_2$ [mg/m³]</th>
<th>CO [mg/m³]</th>
<th>CO freeboard [mg/m³]</th>
<th>$N_2O$ [mg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>886±0.3 (880)</td>
<td>145±0.5</td>
<td>133±0.2</td>
<td>113±0.3</td>
<td>107±0.5</td>
<td>86±0.4</td>
<td>154±0.5</td>
<td>1.15</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>8.7</td>
<td>2.2</td>
<td>2.66</td>
<td>4.9</td>
<td>6.7±0.02</td>
<td>76±0.4</td>
<td>6.7±0.02</td>
<td>76±0.4</td>
</tr>
<tr>
<td></td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
<td>NA*</td>
</tr>
<tr>
<td></td>
<td>4.2±0.14</td>
<td>7.5±0.01</td>
<td>12.6±0.03</td>
<td>13.1±0.08</td>
<td>18.9±0.11</td>
<td>4.2±0.14</td>
<td>7.5±0.01</td>
<td>12.6±0.03</td>
<td>13.1±0.08</td>
</tr>
</tbody>
</table>

* The value was not available for this experiment.

required an additional analyzer. The absence of data of NH₃ and N₂O concentrations in the off-gas and CO concentrations in the freeboard section reported in Tables 3 and 4 was caused by non-availability of the additional FTIR analyzer during the corresponding experimental case.

In all experiments, injection of the reagent resulted in a reduction in nitrogen oxides even at the lowest volumetric flows of the urea solution corresponding to the lowest $NSRs$. The impact of injection of the urea solution on the concentration of NOX in the flue gas downstream of SNCR is demonstrated in Figure 5 with injection of reagent expressed as $NSR$. The NOX reduction efficiency was calculated as the fraction of the difference in the NOX concentration after and before SNCR over the NOX concentration before the SNCR process. The best NOX reduction efficiency of 58% was achieved for temperature 885 °C and $NSR$ 3.1 and this efficiency decreased with the use of higher or lower temperatures. This trend is shown in Figure 5 for four different $NSRs$ in the range from 0.5 to 3.3. NOX reduction was also affected by
Figure 5. Dependence of NO\textsubscript{X} concentration in the flue gas downstream the SNCR on NSR for different temperatures, (L) – lignite, (WP) – wooden pellets.

Figure 6. Dependence of NO\textsubscript{X} reduction efficiency on temperature for different NSRs.

Figure 7. Dependence of NO\textsubscript{X} reduction efficiency on NSR for different temperatures.
the amount of injected reagent, expressed as $NSR$. An increase in $NSR$ resulted in an increase in efficiency for all experiments, although the increase in efficiency of the NO$_x$ reduction gradually decreased with increasing $NSR$, as can be seen in Figure 7, where the dependence of the NO$_x$ reduction efficiency on $NSR$ is given. In the cases where the ammonia slip was measured, the ammonia concentration never exceeded 1 mg/m$^3$ for lignite combustion, even for the highest $NSR$s indicating a strong over-stoichiometry of the urea solution.

N$_2$O is a greenhouse gas. Its emissions in the energy industry are not currently limited in EU legislation, however, they are negatively affected by selective non-catalytic reduction in the case when urea or cyanuric acid is used as the reducing agent [5]. N$_2$O concentrations increased with increasing reagent levels, up to four times its initial value, which can be seen in Tables 5 and 6. In the case of lignite combustion, the highest concentrations of N$_2$O were measured for the highest $NSR$s and freeboard temperatures 880 and 890°C, where the NO$_x$ reduction efficiency was the highest and the concentration of NO$_x$ after SNCR was the lowest. For the freeboard temperature of 890°C and $NSR$ = 3, the concentration of N$_2$O was 73.8 mg/m$^3$, which was 40% of the value of the concentration of NO$_x$. In the case of the combustion of wooden pellets and $NSR$ = 5.1, the concentration of nitrous oxide was 18.9 mg/m$^3$, whereas the concentration of NO$_x$ achieved after reduction was 86 mg/m$^3$. Thus, the application of SNCR with urea solution can possibly be limited by N$_2$O emissions.

The best efficiency of nitrogen oxides reduction is achieved by injecting the reagent into the area with a temperature of around 890°C, which is a lower temperature compared to previous work [5, 19]. This optimal temperature has been found independent of the $NSR$ values. However, to evaluate the effect of temperature on the efficiency of the reduction of NO$_x$, it would be necessary to keep the other remaining combustion parameters constant, which is not feasible due to the control of the combustion process in a pilot-scale boiler. Therefore, the experiments vary not only in different temperatures in the combustion region but also by the flow rate of the fluidized medium and the ratio of secondary to primary air. These parameters may result in different reagent residence times and different mixing for each series of experiments, and may also affect NO$_x$ reduction efficiency. For lignite combustion, the implementation of air staging increases the concentration of carbon monoxide in the flue gas, which can result in a shift of the temperature window for reagent injection into the lower temperature range [5, 20]. In the case of biomass combustion, only primary air and no air staging was used, and the temperature dependence will be the subject of further studies, but a lower initial level of NO$_x$ can lead to lower reduction efficiency.

5. CONCLUSION

This paper presents an experimental study of selective non-catalytic reduction of NO$_x$ in a bubbling fluidized bed boiler. Achieving the required temperatures for the reduction reactions was realized by modifying the combustion process by means of high degree of air staging with sub-stoichiometric conditions in the dense bed, which allowed controlling the freeboard temperature in the required range for the SNCR. In several series of experiments in the BFB boiler, efficient application of selective non-catalytic reduction of nitrogen oxides by injecting the urea solution was achieved. During the experiments, it was possible to achieve a nitrogen oxide reduction efficiency of 59.6% for a normalized stoichiometric excess of reagent 3.0.

High values of $NSR$ resulted in a higher ammonia slip in the flue gas. The optimal temperature for the SNCR in this experimental setup was reached at approximately 890°C, which is a value slightly below the typical optimum reported in the literature. It can be attributed to elevated CO levels in the high-degree air staging operation mode of the combustor. In all experiments, the injection of the reducing agent led to a significant increase in N$_2$O emissions, which in several cases was up to four times the initial value. The NO$_x$ reduction in the case of biomass combustion was nearly 40% but due to the different concentrations of urea solution, the results of lignite and biomass combustion are not directly comparable. Further experiments with biomass as fuel will be the subject of continued research, followed by oxy-fuel combustion of lignite and biomass, i.e., combustion with oxygen as an oxidant.

Acknowledgements

This work was supported by the Ministry of Education, Youth and Sports under OP RD grant number CZ.02.1.01/0.0/0.0/16_019/0000753 “Research center for low-carbon energy technologies”.

References


Experimental verification of the efficiency of SNCR in a BFB


