EXPERIMENTAL VERIFICATION OF THE IMPACT OF THE AIR STAGING ON THE NO\textsubscript{X} PRODUCTION AND ON THE TEMPERATURE PROFILE IN A BFB

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ABSTRACT.

The results of an experimental research on air staging in a bubbling fluidized bed (BFB) combustor are presented within this paper. Air staging is known as an effective primary measure to reduce NO\textsubscript{X} formation. However, in the case of a number of industrial BFB units, it does not have to be sufficient to meet the emission standards. Then selective non-catalytic reduction (SNCR) can be a cost-effective option for further reduction of the already formed NO\textsubscript{X}. The required temperature range at the place of the reducing agent injection for an effective application of the SNCR without excessive ammonia slip is above the temperatures normally attained in BFBs. The aim of this paper is to evaluate the impact of staged air injection on the formation of NO\textsubscript{X} in BFB combustors and to examine the possibility of increasing the freeboard temperature. Several experiments with various secondary/primary air ratios were performed with a constant oxygen concentration in the flue gas. The experiments were carried out using wooden biomass and lignite as fuel in a 30 kW\textsubscript{th} laboratory scale BFB combustor. Furthermore, the results were verified using a 500 kW\textsubscript{th} pilot scale BFB unit. The results confirmed that the air staging can effectively move the dominant combustion zone from the dense bed to the freeboard section, and thus the temperatures for an effective application of the SNCR can be obtained.

KEYWORDS: Air staging, bubbling fluidized bed, NO\textsubscript{X}, SNCR.

1. INTRODUCTION

Nitrogen oxides (NO\textsubscript{X}), particularly NO and NO\textsubscript{2}, are gaseous pollutants that can cause significant environmental issues. One of the main contributors to overall NO\textsubscript{X} emissions is the combustion of solid fuels.

There are three mechanisms of NO\textsubscript{X} formation in the combustion process: the thermal and prompt NO\textsubscript{X} formation mechanism, where the source of NO\textsubscript{X} is atmospheric nitrogen, and the oxidation of fuel-bound nitrogen. Since the breaking of tight N\textsubscript{2}-bond is strongly temperature dependent, the thermal NO\textsubscript{X} formation mechanism (described by Zeldovich et al. \cite{1}) is usually considered important at temperatures higher than 1500°C \cite{2}. Then, the prompt formation of NO\textsubscript{X} (described by Fenimore \cite{3}) can be observed in fuel-rich zones in pre-mixed hydrocarbon flames. The prompt NO\textsubscript{X} formation is also strongly temperature dependent and is relevant from above 1400°C. These conditions are not typical for combustion in bubbling fluidized beds (BFBs) and therefore prompt and thermal NO\textsubscript{X} are of minor importance, and fuel-bound nitrogen is considered to be the main contributor to NO\textsubscript{X} formation there \cite{4,6}. Fuel-bound nitrogen is an important source of NO\textsubscript{X} in the combustion of fossil fuels and biomass. It is particularly important for coal combustion, which typically contains 0.5 – 2.0 \% wt. of nitrogen, and for the combustion of non-wooden biomass, where its content can reach up to 5 \% wt. The degree of conversion of fuel-N to NO\textsubscript{X} is almost independent of the type of nitrogen compound, but is significantly dependent on the local combustion environment \cite{7}. In the furnace, fuel is thermally decomposed and volatile and char compounds are produced. Fuel-bound nitrogen is distributed between char and volatiles, depending on the fuel structure and devolatilisation conditions, such as temperature, heating rate, oxygen concentration, or residence time. In case of lower temperatures or shorter residence times, nitrogen preferably remains in the char, while at higher temperatures, it is part of the volatiles \cite{8}. The mechanisms of volatile-N and char-N conversion were described by Winter et al. \cite{9}, who studied the combustion of a single particle of bituminous coal, subbituminous coal and beech wood in an electrically heated, laboratory-scale, fluidized bed combustor.

The NO\textsubscript{X} reduction can be generally realized using different methods; either by modifying the combustion process itself to suppress the NO\textsubscript{X} formation (so-called primary measures) or applied after the combustion process to decrease the already formed NO\textsubscript{X} (so-called secondary measures). Skopec et al. \cite{3} observed using a 500 kW\textsubscript{th} BFB combustor that the NO\textsubscript{X} formation depends mainly on the excess of oxygen in the combustion zone and slightly also on the fluidized bed temperature. This was also confirmed by Svoboda.
and Pohořelý [10], who studied the formation of NO\textsubscript{X} and N\textsubscript{2}O in a laboratory scale pressurized BFB. They observed that NO\textsubscript{X} formation was strongly promoted by an increase in air stoichiometry (while N\textsubscript{2}O formation was depressed) at atmospheric pressure. They also observed that an increase in the temperature of the fluidized bed slightly promotes the formation of NO\textsubscript{X} and decreases the formation of N\textsubscript{2}O under slightly elevated pressure (0.25 MPa). Therefore, the primary measures reduce the temperature and oxygen concentration in the furnace and subsequently allow the oxidation of the remaining combustibles above the furnace. As primary measures, staged injection of air or fuel and flue gas recirculation could be used. Fuel staging requires secondary gas phase fuel and it is not a practically applied method for BFBs.

In the case of staged air injection, the oxidizer is separated into two or even more streams. The first stream is introduced into the BFB as the primary air (possibly mixed with the FGR). The second stream (and possibly the consequent streams) is introduced into the freeboard section above the fluidized bed. In the primary combustion zone, there are fuel-rich conditions (stoichiometric or even sub-stoichiometric oxygen/fuel ratio) that cause a smaller conversion of the NO\textsubscript{X} precursor to NO\textsubscript{X}, and favor the formation of N\textsubscript{2}. Furthermore, the already formed NO can be further reduced through a) reburning reactions with the released fuel N (mainly HCN and NH\textsubscript{3}), or b) through reactions with carbon compounds that were not yet completely oxidized, or c) on the char surface through catalytic reactions [11] [12]. Gaseous products of incomplete combustion (CO and TOC), which are inevitably formed under such conditions, are subsequently oxidized in the freeboard section, where the secondary oxidizer is introduced. The efficiency of NO\textsubscript{X} reduction through staged injection of air is significantly dependent on the residence time in the primary zone with sub-stoichiometric (reduction) conditions [12] [13]. The optimum residence time in the sub-stoichiometric zone may vary according to the fuel structure. For a lignite coal, it is about 1.5 s [13]. If the residence time in the this zone is too short, NO can further form in a significant amount in the secondary oxidation zone [12]. Sirisomboon and Charernporn [14] also observed that the relative reduction efficiency of the staged air injection depends on the overall stoichiometry of the combustion air. With the most extensive air staging, they observed a similar reduction of about 70 ppmv of NO at all air excess ratios (in the range from 20 to 80%). Since the formation of NO\textsubscript{X} is strongly affected by overall air stoichiometry, the reduction efficiency was higher for lower excess of air and lower for higher excess of air.

Secondary measures are mainly selective non-catalytic (SNCR) and selective catalytic reduction (SCR). These flue gas treatments use reducing agents containing NH\textsubscript{2} (ammonia, urea, ammonia water, etc.), which can reduce NO. The reduction follows

\begin{equation}
2\text{NO} + 2\text{NH}_3 + \frac{1}{2}\text{O}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O} \quad (1)
\end{equation}

and

\begin{equation}
2\text{NO} + \text{CO} (\text{NH}_2)_2 + \frac{1}{2}\text{O}_2 \rightarrow 2\text{N}_2 + \text{CO}_2 + 3\text{H}_2\text{O} \quad (2)
\end{equation}

The effective operation of SNCR without excessive ammonia slip is determined by an optimal temperature range for the injection of the reducing agent into the combustor. The ideal temperature range depends on the reducing agent used, which can be seen in Figure 1. However, the required temperature range 900 – 1000 °C is normally achieved neither in the bed nor in the freeboard in BFBs.

The catalyst present in the SCR systems usually allows achieving higher reduction efficiency at significantly lower temperatures compared to SNCR technology, but at a high investment cost.

Air staging, which partly moves the combustion zone from the dense bed zone to the freeboard of the BFB, appears to be a suitable measure for increasing the freeboard temperature to the required temperature range. Sirisomboon and Charernporn [14] increased the temperature in the freeboard section of a pilot scale BFB of about 100 °C through air staging and reached up to 1100 °C using high volatile sunflower shells as fuel.

Although NO\textsubscript{X} formation and possible reduction paths in BFBs have been studied by a number of authors using multiple fuels and various scales of devices, the possible application of SNCR in BFBs has not been of significant interest yet.

This paper presents a comprehensive experimental study of the impact of staged air supply on NO\textsubscript{X} formation in a BFB and on the temperature profile within
the combustor as a consequence of sub-stoichiometric combustion in the dense bed and subsequent oxidation of the remaining combustibles in the freeboard section in order to be able to define the process conditions for reaching the SNCR optimal temperature range. A number of experiments were performed combusting lignite and wooden pellets in various operating regimes of a 30 kWth BFB experimental facility. Furthermore, to validate the results and their applicability to the industrial scale, the same experiments were performed in a 500 kWth pilot-scale BFB combustor.

2. EXPERIMENTS

2.1. EXPERIMENTAL SETUP

The 30 kWth experimental facility has been comprehensively described elsewhere [16] and so it will be described only briefly here. Its scheme is given in Figure 2. The facility is 2 m high, has a rectangular cross-section, and is made of stainless steel insulated from the outside using the 50 mm thick Insulfrax board in the fluidized bed section and using mineral wool in the freeboard section. There are no internal heat exchangers in the facility.

Volumetric flows of primary and secondary air were measured using two rotameters. The temperature profile along the height of the facility was measured using five thermocouples in the dense bed region and three thermocouples in the freeboard region. Directly in the fluidized bed, the temperature was measured with two thermocouples. However, the value of only one placed 166 mm above the fluidizing gas distributor was taken as representative. Primary air with real flue gas recirculation were used to provide sufficient fluidization, and secondary air was introduced at the beginning of the freeboard section. The flue gas was continuously sampled and the volumetric fractions of CO₂, CO, SO₂ and NOₓ were measured using a NDIR sensors, while the volumetric fraction of O₂ was measured using a paramagnetic sensor.

The scheme of the 500 kWth pilot scale BFB boiler is given in Figure 3. This boiler consists of three main sections: the combustion chamber with freeboard, the crossover pass, and the heat exchanger. The fluidization gas, formed by primary air and recirculated flue gas, enters the bed trough distributor consisting of 36 nozzles placed in 6 rows. The combustion chamber and the freeboard section have a cylindrical cross section and are insulated with a fireclay lining with a water-cooled surface. In the freeboard area, the facility is equipped with 6 thermocouples along the height. Secondary air is supplied to the freeboard section by 4 distributors placed evenly on a perimeter, and each distributor can provide the secondary air inlet at 4 different heights. For the experiments, secondary air inlets at a height of 550 mm above the fluidized bed were used. From the freeboard section, the flue gas continues to the empty crossover pass.
with water-cooled surface and then enters the heat exchanger. The flue gas was continuously sampled and the volumetric fractions of CO₂, CO, SO₂ and NOₓ were measured using NDIR sensors, while the volumetric fraction of O₂ was measured using a paramagnetic sensor.

### 2.2. Materials

The experiments were carried out using Czech lignite Bílina HP1 135 and pellets from spruce wood as fuel. The proximate and ultimate analyses of lignite and wooden pellets are given in Table 1. Lignite has a significantly higher nitrogen content compared to spruce wood, so the NOₓ yields should also be higher in case of combustion of lignite. Spruce wood combustibles contain about 100% more volatiles compared to lignite, which should move the dominant combustion zone slightly higher in the facility in case of wood combustion. For experiments carried out using the 30 kWth facility, the lignite was sieved to a particle size of up to 7 mm. The lignite ash was used as a bed material in the case of lignite combustion. Biomass combustion experiments were carried out using spruce wood pellets (according to the ENplus A1 standard) and using a lightweight ceramic aggregate (LWA) as an external bed material. The physical properties of the bed materials are given in Table 2. The arithmetic mean, mode, median, 1st decile (d₁₀), and 9th decile (d₉₀) particle size were evaluated. The density and bulk density were analyzed along with the particle size. The lignite ash can be classified as Geldart B particles which are well fluidizable and form vigorous bubbles. The used LWA population referred as ‘0–2’ is on the boundary between B and D particle types in the Geldart classification, where the class D particles are difficult to fluidize in deep beds, they spout, form exploding bubbles or channels [17].

From the analysis of the particle size distribution (PSD), the minimum fluidization velocity, the minimum complete fluidization velocity (defined as uₘₐₓ calculated for the particle size d₉₀, and the terminal particle velocity were evaluated for two different conditions of the fluidization gas. The numerical approach was taken from [15]. First, the gas properties corresponded to air at 20°C (ρₚ = 1.20 kg m⁻³, η = 1.8 · 10⁻⁵ Pa s) and secondly to air at 850°C (ρₚ = 0.29 kg m⁻³, η = 3.8 · 10⁻⁵ Pa s). The fluidizing gas temperature of 850°C was chosen, because when the fluidizing gas passes through the bed of hot material, it is heated to the bed temperature within a few millimeters above the fluidizing gas distributor [19]. The minimum fluidization velocities of both bed materials were also experimentally verified by measuring the correlation of bed pressure drop and superficial fluidizing gas velocity u₀. This method can be found in [15]. This test was carried out using air at 20°C as fluidization gas. The calculated minimum fluidization velocities, the complete fluidization velocities, and the terminal velocities, as well as the experimentally determined minimum fluidization velocities, are given in Table 3.

### 2.3. Methods

To evaluate the impact of staged air supply on NOₓ emissions and on the temperature profile within the BFB combustor in consequence of the substoichiometric combustion in the dense bed and subsequent oxidation of the remaining combustibles in the freeboard, two series of experiments were performed using the 30 kWth BFB experimental facility and using lignite and biomass as fuels. Furthermore, a series of experiments was done using the 500 kWth pilot scale facility and only using lignite as fuel. To highlight this impact and reduce the side effects of fluidized bed temperature, the experiments were carried out with a constant bed temperature of 880°C and the oxygen level in the dry flue gas maintained at 8% for wooden pellets and at 6% for lignite for both facilities. The bed temperature was controlled through the change of volumetric flow or of the composition of the fluidizing gas, which consisted of primary air and recirculated flue gas.
The degree of the combustion air staging can be described using Equation 3

\[ \psi = \frac{V_{air,sec}}{V_{air,prim}}, \]  

where \( V_{air,sec} \) is the volumetric flow of secondary air and \( V_{air,prim} \) is the volumetric flow of primary air.

In the experiments performed using 30 kWth BFB facility, one case without air staging was measured as a reference for both fuels and then the following four cases with an increasing secondary/primary air ratio \( \psi \) to 2.75 were measured. The minimum amounts of primary and secondary air were limited by the flowmeters used for the volumetric flows measurement and were set to 10 m³/h. The step for increment of the secondary air flow was 6 m³/h. However, to keep the overall oxygen level constant and maintain the bed temperature and sufficient fluidization, it was not possible to exactly keep the required secondary/primary air ratio constant throughout. A reference case without air staging and three cases with an increasing secondary/primary air ratio \( \psi \) up to 1.6 were performed using the 500 kWth pilot-scale facility.

### Table 3. Minimum fluidization velocities \( u_{mf} \), terminal velocities \( u_t \) (calculated for \( d_{mean} \)), minimum velocities of complete fluidization \( u_{mf-90} \), and complete terminal velocities \( u_{t-90} \) (calculated for \( d_{50} \)) of the selected fluidized bed materials. The experimental values are in brackets.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Lignite ash</th>
<th>LWA 0–2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calculation (experimental) results</td>
<td></td>
</tr>
<tr>
<td>air at 20 °C</td>
<td>( u_{mf} ) m s⁻¹</td>
<td>0.37 (0.42)</td>
</tr>
<tr>
<td></td>
<td>( u_{mf-90} ) m s⁻¹</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>( u_t ) m s⁻¹</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>( u_{t-90} ) m s⁻¹</td>
<td>5.47</td>
</tr>
<tr>
<td>air at 850 °C</td>
<td>( u_{mf} ) m s⁻¹</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>( u_{mf-90} ) m s⁻¹</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td>( u_t ) m s⁻¹</td>
<td>2.36</td>
</tr>
<tr>
<td></td>
<td>( u_{t-90} ) m s⁻¹</td>
<td>10.23</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

The results of biomass and coal combustion in the 30 kWth facility (given in Figures 4 and 5 and Tables 4 and 5) show that the air staging positively affected NOX concentration in the flue gas and the NOX formation was suppressed with a higher secondary/primary air ratio. On the other hand, the CO level increased significantly, as can be seen in Figures 4 and 5. This could be caused by the decrease in excess oxygen to a sub-stoichiometric atmosphere in the fluidized bed region (\( \lambda_{prim} < 1 \)) connected with incomplete combustion and increased CO production, which is then not oxidized effectively in the freeboard region, possibly due to lower temperatures there. Therefore, the application of air staging from this point of view is limited by acceptable CO emissions. Unfortunately, the flue gas temperature significantly decreased as

### Figure 4. The dependence of the NOX and CO volumetric concentration in dry flue gas on the ratio of the secondary to primary air volumetric flows \( \psi \) in the case of a lignite combustion in the 30 kWth BFB facility. The gaseous pollutants concentrations related to 6% vol. of O2 in dry flue gas.

### Figure 5. The dependence of the NOX and CO volumetric concentration in dry flue gas on the ratio of the secondary to primary air volumetric flows \( \psi \) in the case of a biomass combustion in the 30 kWth BFB facility. The gaseous pollutants concentrations related to 6% vol. of O2 in dry flue gas.
Experimental results of the staged supply of air on the NOX formation in the case of lignite combustion in the 30 kWth BFB facility. Gaseous pollutant concentrations are related to 6 % vol. of O2 in dry flue gas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>‘Case 1’</th>
<th>‘Case 2’</th>
<th>‘Case 3’</th>
<th>‘Case 4’</th>
<th>‘Case 5’</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi )</td>
<td>[-]</td>
<td>0.0</td>
<td>0.35</td>
<td>0.62</td>
<td>1.23</td>
<td>2.45</td>
</tr>
<tr>
<td>( \lambda_{prim} )</td>
<td>[-]</td>
<td>1.4</td>
<td>1.04</td>
<td>0.8</td>
<td>0.68</td>
<td>0.48</td>
</tr>
<tr>
<td>( \phi_{O_2} )</td>
<td>[% vol.]</td>
<td>5.9 ± 0.03</td>
<td>5.93 ± 0.03</td>
<td>5.96 ± 0.03</td>
<td>6.09 ± 0.03</td>
<td>6.13 ± 0.01</td>
</tr>
<tr>
<td>( t_{BFB} )</td>
<td>[°C]</td>
<td>881 ± 0.6</td>
<td>889 ± 0.3</td>
<td>886 ± 0.3</td>
<td>890 ± 0.4</td>
<td>887 ± 0.3</td>
</tr>
<tr>
<td>( C_{NOX} )</td>
<td>[mg·m⁻³]</td>
<td>635 ± 1</td>
<td>491 ± 2</td>
<td>423 ± 1</td>
<td>328 ± 1</td>
<td>266 ± 0</td>
</tr>
<tr>
<td>( C_{CO} )</td>
<td>[mg·m⁻³]</td>
<td>277 ± 7</td>
<td>347 ± 4</td>
<td>451 ± 1</td>
<td>1038 ± 5</td>
<td>2155 ± 8</td>
</tr>
<tr>
<td>( u_0 )</td>
<td>[m·s⁻¹]</td>
<td>1.73</td>
<td>1.73</td>
<td>1.86</td>
<td>1.71</td>
<td>1.71</td>
</tr>
<tr>
<td>( m_{fuel} )</td>
<td>[kg·h⁻¹]</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>

The impact of air staging on the temperature profile in the 30 kWth combuster can be seen in Figures 4 and 5 and on the temperature profile in the 500 kWth combuster in Figure 7.

In the case of the 30 kWth combuster, it was not possible to achieve the temperatures required for SNCR while keeping the bed temperature constant for coal combustion. In the best scenario (for the secondary/primary air ratio \( \psi \) 1.4), the temperature rose by 10°C in a small area directly above the fluidized bed, but this could also be caused by not exactly the same fluidized bed temperature. In general, no significant positive impact was observed from the increase in secondary air supply. In the case of biomass

the gas passed through the facility due to poor insulation of the freeboard section of the 30 kWth BFB facility. If the temperature is too low at the point of secondary air injection, the oxidation of the unburned combustibles is very slow, which reduces the desired effect of air staging.

Since both the fluidized bed and the freeboard section are well insulated by the fireclay lining in the 500 kWth facility, the freeboard temperatures are significantly higher compared to the 30 kWth facility. Therefore, secondary air properly oxidizes CO and other incomplete combustion products and the concentration of CO does not increase (moreover, it decreases) with an increasing secondary/primary air ratio \( \psi \), as can be seen in Figure 4 and Table 5, where the results of lignite combustion in the 500 kWth BFB facility are given. Based on the rise in the NOX concentration in flue gas related to the increase in the secondary/primary air ratio \( \psi \) from 0.92 to 1.59 in Figure 6, it can be estimated that the NOX reduction through the air staging has an optimum at the value of the secondary/primary air ratio \( \psi \) about 1. The further NOX reduction observed in the results obtained using the 30 kWth facility can then be explained by the increased CO concentration.

The impact of air staging on the temperature profile in the 30 kWth combuster can be seen in Figures 4 and 5 and on the temperature profile in the 500 kWth combuster in Figure 7.

In the case of the 30 kWth combuster, it was not possible to achieve the temperatures required for SNCR while keeping the bed temperature constant for coal combustion. In the best scenario (for the secondary/primary air ratio \( \psi \) 1.4), the temperature rose by 10°C in a small area directly above the fluidized bed, but this could also be caused by not exactly the same fluidized bed temperature. In general, no significant positive impact was observed from the increase in secondary air supply. In the case of biomass
with insulation improvement, air staging would also
velocity in the freeboard section moved the highest
temperature in the height profile further in
and Charenporn [14] is also in agreement with the findings of Sirisomboon
the flue gas stream. The increased temperature in the
increased volumetric flow, as the higher flow rate is
then associated with heat loss. It can be expected that
with insulation improvement, air staging would also
increase the freeboard temperature for coal combustion,
because it did so in the 500 kWth facility, where
both the fluidized bed and the freeboard section are
insulated using an inner fireclay lining. As can be seen in
Figure 7 where the dependence of the temperature
height profile on the secondary/primary air ratio \( \psi \)
is given, staged air injection can move the dominant
combustion zone from the furnace to the freeboard
section and therefore could increase the freeboard
temperature sufficiently for efficient application of SNCR
in the BFB boilers even in the case of a lignite combustion.
The most significant increase in freeboard
combustion, enhanced combustion of volatiles above
the fluidized bed was observed with an increase in
the secondary/primary air ratio, causing a considerable
increase in temperature. There, a temperature
greater than 900 °C was reached, thus conducive conditions
could be provided for the application of SNCR,
although the secondary/primary air ratio must be
high. However, a significant decrease in freeboard
temperatures can be observed for both biomass and
combustion in Figures 7 and 8 possibly due to
insufficient insulation of the freeboard section. The
negative impact of staged air supply can be caused by
increased volumetric flow, as the higher flow rate is
then associated with heat loss. It can be expected that
with insulation improvement, air staging would also
increase the freeboard temperature for coal combustion,
because it did so in the 500 kWth facility, where
both the fluidized bed and the freeboard section are
insulated using an inner fireclay lining. As can be seen in
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temperature sufficiently for efficient application of SNCR
in the BFB boilers even in the case of a lignite combustion.
The most significant increase in freeboard

### Table 6. Experimental results of the staged supply of air on the NO\(_x\) formation in the case of lignite combustion in the 500 kWth BFB facility. Gaseous pollutants concentrations are related to 6% vol. of O\(_2\) in dry flue gas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>‘Case 1’</th>
<th>‘Case 2’</th>
<th>‘Case 3’</th>
<th>‘Case 4’</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi )</td>
<td>[-]</td>
<td>0.0</td>
<td>0.48</td>
<td>0.91</td>
<td>1.6</td>
</tr>
<tr>
<td>( \lambda_{prim} )</td>
<td>[-]</td>
<td>1.19</td>
<td>0.7</td>
<td>0.66</td>
<td>0.57</td>
</tr>
<tr>
<td>( \phi_{O_2} )</td>
<td>[% vol.]</td>
<td>6.06 ± 0.06</td>
<td>5.27 ± 0.04</td>
<td>4.75 ± 0.04</td>
<td>5.73 ± 0.07</td>
</tr>
<tr>
<td>( t_{BFB} )</td>
<td>[°C]</td>
<td>887 ± 0.7</td>
<td>885 ± 0.5</td>
<td>878 ± 0.6</td>
<td>879 ± 0.4</td>
</tr>
<tr>
<td>( C_{NO_x} )</td>
<td>[mg · m(^{-3})]</td>
<td>256 ± 2</td>
<td>186 ± 1</td>
<td>173 ± 1</td>
<td>253 ± 1</td>
</tr>
<tr>
<td>( C_{CO} )</td>
<td>[mg · m(^{-3})]</td>
<td>4314 ± 209</td>
<td>2882 ± 206</td>
<td>3118 ± 236</td>
<td>499 ± 81</td>
</tr>
<tr>
<td>( u_0 )</td>
<td>[m · s(^{-1})]</td>
<td>1.71</td>
<td>1.29</td>
<td>1.02</td>
<td>1.26</td>
</tr>
<tr>
<td>( N - NO )</td>
<td>[% mole]</td>
<td>8.72</td>
<td>6.32</td>
<td>5.87</td>
<td>8.63</td>
</tr>
<tr>
<td>( m_{fuel} )</td>
<td>[kg · h(^{-1})]</td>
<td>50.0</td>
<td>55.0</td>
<td>46.0</td>
<td>62.0</td>
</tr>
</tbody>
</table>

Figure 7. The dependence of the temperature height profile within the 30 kWth BFB facility on the ratio of the secondary to primary air volumetric flows \( \psi \) in the case of a lignite combustion. The horizontal dash-and-dot line represents the height where the secondary air is injected.

Figure 8. The dependence of the temperature height profile within the 30 kWth BFB facility on the ratio of the secondary to primary air volumetric flows \( \psi \) in the case of a biomass combustion. The horizontal dash-and-dot line represents the height where the secondary air is injected.
The aim of the work was to experimentally verify the impact of air staging on NOX emissions from combustion of coal and wooden biomass in BFB and to study the feasibility of providing sufficient conditions for the application of selective non-catalytic reduction of nitrogen oxides in BFB using two experimental combustors with thermal load 30 and 500 kWth.

The experiments also showed that air staging itself is an effective primary measure for BFB to reduce NOX formation. In the results from the 30 kWth facility, the suppression of the NOX directly correlated with an increased secondary/primary air flow ratio. The NOX emissions reduction efficiency of about 55% and 40% was achieved in the case of lignite and biomass combustion, respectively. In the experiments carried out using the 500 kWth facility, the best NOX emissions reduction efficiency of 33% was achieved for the secondary/primary air ratio ψ 0.92 and its further increase did not bring further NOX reduction.

Due to the poor insulation of the freeboard section of the 30 kWth BFB facility, it was not possible to increase the freeboard temperature to a value higher than the fluidized bed temperature for both fuels used. In the case of biomass combustion, the results confirmed that it is possible to reach the suitable temperature range for the SNCR of NOX by air staging, but the secondary/primary air ratio must be significantly high, resulting in sub-stoichiometric conditions in the dense bed. However, a temperature increase was observed only in the well-insulated fluidized bed region below the secondary air inlets. For coal combustion, no positive impact of staged injection of combustion air was observed in the 30 kWth facility. The experiments carried out with 500 kWth BFB facility showed that if the combustion chamber and the freeboard section are properly insulated, the freeboard temperature increases with the increase of the secondary/primary air ratio. The ideal value of this ratio was approximately 1, for which the freeboard temperature was about 70°C higher than the fluidized bed temperature. It can be expected that with insulation improvement of the 30 kWth facility, the air staging would have a positive impact on the temperature profile for combustion of both fuels.

Recently, the insulation of the freeboard section of the 30 kWth BFB facility was replaced with Insulfrax boards. Further experiments confirmed that temperature height profiles within the combustor are significantly improved. This study will continue with the characterization of the formation of gaseous pollutants in combustion of alternative biomass fuels in a BFB. In addition, the application of SNCR in the 500 kWth BFB combustor will be studied.

4. CONCLUSION

The aim of the work was to experimentally verify the impact of air staging on NOX emissions from combustion of coal and wooden biomass in BFB and to study the feasibility of providing sufficient conditions for the application of selective non-catalytic reduction of nitrogen oxides in BFB using two experimental combustors with thermal load 30 and 500 kWth.

4.1. Combustion tests

The experiments carried out using the 500 kWth facility, the best NOX emissions reduction efficiency of 33% was achieved for the secondary/primary air ratio ψ 0.92 and its further increase did not bring further NOX reduction.

4.2. Air staging

Due to the poor insulation of the freeboard section of the 30 kWth BFB facility, it was not possible to increase the freeboard temperature to a value higher than the fluidized bed temperature for both fuels used. In the case of biomass combustion, the results confirmed that it is possible to reach the suitable temperature range for the SNCR of NOX by air staging, but the secondary/primary air ratio must be significantly high, resulting in sub-stoichiometric conditions in the dense bed. However, a temperature increase was observed only in the well-insulated fluidized bed region below the secondary air inlets. For coal combustion, no positive impact of staged injection of combustion air was observed in the 30 kWth facility. The experiments carried out with 500 kWth BFB facility showed that if the combustion chamber and the freeboard section are properly insulated, the freeboard temperature increases with the increase of the secondary/primary air ratio. The ideal value of this ratio was approximately 1, for which the freeboard temperature was about 70°C higher than the fluidized bed temperature. It can be expected that with insulation improvement of the 30 kWth facility, the air staging would have a positive impact on the temperature profile for combustion of both fuels.

Recently, the insulation of the freeboard section of the 30 kWth BFB facility was replaced with Insulfrax boards. Further experiments confirmed that temperature height profiles within the combustor are significantly improved. This study will continue with the characterization of the formation of gaseous pollutants in combustion of alternative biomass fuels in a BFB. In addition, the application of SNCR in the 500 kWth BFB combustor will be studied.

4.3. Conclusions

The experiments also showed that air staging itself is an effective primary measure for BFB to reduce NOX formation. In the results from the 30 kWth facility, the suppression of the NOX directly correlated with an increased secondary/primary air flow ratio. The NOX emissions reduction efficiency of about 55% and 40% was achieved in the case of lignite and biomass combustion, respectively. In the experiments carried out using the 500 kWth facility, the best NOX emissions reduction efficiency of 33% was achieved for the secondary/primary air ratio ψ 0.92 and its further increase did not bring further NOX reduction.

Due to the poor insulation of the freeboard section of the 30 kWth BFB facility, it was not possible to increase the freeboard temperature to a value higher than the fluidized bed temperature for both fuels used. In the case of biomass combustion, the results confirmed that it is possible to reach the suitable temperature range for the SNCR of NOX by air staging, but the secondary/primary air ratio must be significantly high, resulting in sub-stoichiometric conditions in the dense bed. However, a temperature increase was observed only in the well-insulated fluidized bed region below the secondary air inlets. For coal combustion, no positive impact of staged injection of combustion air was observed in the 30 kWth facility. The experiments carried out with 500 kWth BFB facility showed that if the combustion chamber and the freeboard section are properly insulated, the freeboard temperature increases with the increase of the secondary/primary air ratio. The ideal value of this ratio was approximately 1, for which the freeboard temperature was about 70°C higher than the fluidized bed temperature. It can be expected that with insulation improvement of the 30 kWth facility, the air staging would have a positive impact on the temperature profile for combustion of both fuels.

Recently, the insulation of the freeboard section of the 30 kWth BFB facility was replaced with Insulfrax boards. Further experiments confirmed that temperature height profiles within the combustor are significantly improved. This study will continue with the characterization of the formation of gaseous pollutants in combustion of alternative biomass fuels in a BFB. In addition, the application of SNCR in the 500 kWth BFB combustor will be studied.

ACKNOWLEDGEMENTS

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

LIST OF SYMBOLS

BFB bubbling fluidized bed
LHV low heating value
LWA lightweight ceramic aggregate
PSD particle sized distribution
SCR selective catalytic reduction
SNCR selective non-catalytic reduction
C[CO] concentration of CO in the dry flue gas [mg/m3]
C[NOx] concentration of NOX in the dry flue gas [mg/m3]
d[90] 1st decile particle size [mm]
d[90] 9th decile particle size [mm]
d[50] median diameter [mm]
d[mean] mean particle size [mm]
d[mode] mode particle size [mm]
h height [mm]
fuel load [kg h−1]
N→NO conversion ratio of fuel nitrogen to NO [% mole]
t temperature [°C]
t[BA] temperature in the bubbling fluidized bed [°C]
u[f] superficial gas velocity [m s−1]
u[f, 90] minimum fluidization velocity [m s−1]
u[f, 90] minimum fluidization velocity for d[90] [m s−1]
u[t] terminal particle velocity [m s−1]
u[t] terminal particle velocity [m s−1]
V[air, prim] volumetric flow of primary air [m3/h]
V[air, sec] volumetric flow of secondary air [m3/h]
λ[air] ratio of the air excess in the primary combustion zone [−]
ϕ[O2] volumetric fraction of O2 in dry flue gas [% vol]
ρ[s] density of solid material [kg m−3]
ρ[b] bulk density of solid material [kg m−3]
ψ ratio of the secondary to primary air volumetric flows [−]
References


