

A Scale-Up Project for Operating a 115 MW_{th} Biomass-Fired CFB boiler with Oxygen Carriers as Bed Material

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Abstract – Oxygen Carrier Aided Combustion (OCAC) is a concept that uses an oxygen-active bed material to increase the overall efficiency in fluidized bed (FB) combustors. The introduction of oxygen carriers (OCs) in existing FB plants is an attractive opportunity to investigate OCs under industrially-relevant conditions at a low economic risk. In this way, important experience and knowledge of the physio-chemical properties of OCs can be gained during long-term operation, which in turn can be used for the scale-up of oxygen-looping techniques, e.g. chemical-looping combustion. The overall aim of this experimental study was to investigate, develop and collect data to increase the knowledge of how OCs can be deployed in commercial FB boilers, while at the same time granting the plant operator benefits from an increased revenue. This paper summarizes the first results from an experimental campaign performed during three weeks of OCAC operation in a 115 MW_{th} commercial CFB boiler, which is fired with a mix of recycled waste-wood and wood chips. During the campaign, the silica-sand bed material was gradually replaced by the mineral ilmenite. It was shown that ilmenite operation, in comparison to operation with silica-sand, facilitated a reduction in the air surplus by as much as 30 %, while increasing the boiler load from 115 MW_{th} to 123 MW_{th}. During ilmenite operation no problems related to the external or internal bed-material logistics nor in the overall boiler operation. However, during ilmenite operation slightly higher emissions of NO_x and consumption of ammonia were detected in comparison to operation with silica-sand.

1 Introduction

Thermal conversion of solid fuels, mainly through combustion, is one of the cornerstones of industry in our society with applications in many sectors as well as for transportation and utility industries. For combustion, fossil-based fuels, such as coal, are by far the largest source of energy worldwide. Nevertheless, at an alarming increase in anthropogenic CO₂ emissions, paralleled by global warming, new technologies are required that can convert fuels in nitrogen-free atmospheres so that CO₂ can be efficiently separated and used for new products or for storage purposes. Chemical-looping combustion (CLC) is a novel technique that could potentially provide this nitrogen-free fuel conversion to enable efficient Carbon Capture and Storage (CCS) in large-scale power plants [1]. The research output on CLC and the number of active research groups has increased rapidly during the last decade, but in principle all experimental research is still done on a lab-scale. This means that to challenge existing air-fired combustion techniques there is still a great need for research and development to scale-

up and achieve commercial status of CLC. One of the major obstacles to overcome is the need to prove efficient operation and logistics for oxygen carriers (OCs) under industrially-relevant conditions. The following work addresses this issue and demonstrates a path to increase the knowledge and industrial acceptance of OCs by deploying these in existing fluidized bed (FB) plants via the so-called Oxygen Carrier Aided Combustion (OCAC) concept [2].

FB combustion technology experienced a large growth in the late 1970s with the aim of improving conversion and flexibility of solid fuels in thermal power plants, mainly for the conversion of complex coals. The base of this combustion technique lies in the utilization of a bed material acting as a heat carrier during fuel conversion [3]. In FB combustion, fuel particles are suspended in a hot bed of inert solids, which is fluidized by means of the combustion air. This results in a bed that behaves as fluid, yielding high mixing of gas and solids as well as promoting rapid heat transfer and efficient fuel conversion within the bed. Circulating fluidized bed (CFB) plants can burn a large range of low-grade solid fuels, including difficult fuels such as woody biomass and low-grade coals, at a high efficiency and without the need of expensive pulverization of the fuel. The bed material used for combustion of biomass and waste is usually silica-sand, which is an inert material, meaning that the material does not possess any oxygen-transporting capability. Today, FB combustion is an industrially-accepted technology with approximately 5000 MW thermal capacity installed in Sweden and around 30 000 MW thermal capacity installed in other countries in Europe. Significant capacities are also found in North America and China.

A high conversion of the fuel is a necessary step not only to comply with regulations but also to reach a high fuel-to-fluid efficiency. In contrast to coal, the high volatiles contents of biomass and waste create a greater challenge for the mixing of gaseous oxygen and fuel components, both on macroscopic and microscopic scales, whereas reactions between fuel and oxygen are to a large extent controlled by this mixing. This creates a challenge for fuels with high volatile content, as the time scale for the release of volatiles compared to the time scale for lateral mixing of solids causes an increased concentration of volatiles close to the wall, where the fuel is introduced [4-6], creating a volatile-rich and a volatile-poor region.

Recently, researchers at Chalmers University of Technology demonstrated a combustion concept, more known as OCAC [1], to abate in-furnace mixing issues. In OCAC the robustness of FB combustion is combined with the novelty of using oxygen-active materials from chemical-looping systems. By replacing the commonly used bed material silica-sand with oxygen-active metal oxides during biomass combustion, the overall oxygen distribution in the furnace can be increased. The oxygen-carrying material can absorb and release oxygen during redox reactions at the temperatures used. Owing to its reactions with combustibles and the fluid dynamics in the riser furnace, this, in theory, facilitates simultaneous oxygen supply across the entire boiler geometry [7]. This continuous redox sequence results in a net transport of oxygen, which, is the very same phenomenon that CLC operation is based upon. In other words, the use of an oxygen-active bed material in a common FB boiler results in the transport of oxygen from oxygen-rich zones to oxygen-poor zones in the furnace, which causes the combustion operation to be carried out at a more uniform temperature and which creates a more homogeneous combustion process as compared to using silica-sand as bed material.

A great advantage of the oxygen transport is a significant reduction of the air surplus needed to achieve a sufficiently high burnout of the fuel and, hence, a reduction of the heat loss with the hot flue gas leaving the boiler. Together with E.ON, OCAC operation using ilmenite as bed material has been adopted in two commercial FB boilers fired with municipal solid waste (75 MW and 85 MW), where one of the boilers has been operated continuously for more than 20 000 h [8]. Beside the oxygen-carrying properties, ilmenite also possesses magnetic properties, i.e. it can be attracted by a magnetic field and can thus be separated from non-magnetic bed ashes [9]. The first magnetic separation unit for enhanced ilmenite recovery in FB systems has been installed in the municipal solid waste-fired E.ON plant (75 MW) in Norrköping, Sweden.

This paper will detail the first experiences from a scale-up project, where the OCAC concept is operated for three weeks during April 2018 in a large-scale, commercial, biomass-fired CFB boiler (115 MW) at the Örtöfta plant.

2 Experimental

The Örtöfta CFB plant is owned by the company Krafringen, which is a local utility company in Southern Sweden. The three-week-long experiment was led by researchers from Chalmers University of Technology and Improb AB, and Krafringen supported the experiments by providing staff that operated the boiler and helped during the trials.

2.1 Boiler details

The Örtöfta plant was designed and built by Foster Wheeler Energi AB (now: Amec Foster Wheeler) and has been in operation since March 2014. The plant consists of a biomass-fired CHP cycle (112 bar, 540 °C) with a nominal thermal capacity of 115 MW_{th} (steam turbine: 38-40 MW_{el}, turbine condenser: 72 MW_{th}, flue gas condenser: 16-18 MW_{th}). The turbine condenser and the flue gas condenser supply heat to the local district-heating grid. The amount of bed material in the system is about 60 t under normal operation and 15-20 t during start-up. The bed material is separated from the flue gases in two parallel gas-solid separators and then returned to the furnace via two separate loop-seals. The cross-section of the furnace is 2.2 m x 8.8 m at the height of the fluidization nozzles and expands to 5.5 m x 8.8 mm in the upper part of the furnace. The height from the bottom of the furnace to its roof is 28.4 m. Furnace and separators are equipped with ammonia injection (SNCR) systems to reduce the emissions of NO_x. The loop seals include submerged steam super-heaters, which are of the INTREXTM (integrated heat exchanger) type. Blower engines are used to fluidize the loop seals and provide a pressure between 30 kPa and 70 kPa (50 kPa in normal mode). The boiler is also equipped with flue gas recirculation to control the temperatures in the furnace and increase flexibility.

After the flue gases are cooled in the convection path, remaining particles are separated using textile filters. The last available heat is then extracted via the flue gas condenser before the flue gases are released to the atmosphere via the stack.

The boiler is normally operated with silica-sand as bed material, where the sand has an average particle size of 0.25 mm and is delivered in bulk trucks to the plant's silo, which has a

capacity of 40-45 m³. The boiler is equipped with a drum sieve for bed-material recovery, where the accept fraction from the bed ash is directly sent back to the furnace and the reject stream is sent to ash containers.

The fuel during the experiment consisted in a mix of recycled waste-wood and wood chips with an average moisture content around 40 wt.% and a heating value of around 10.5 MJ/kg, as received.

The oxygen concentration in the flue gases is used to control the boiler system, and it is measured before the economizer section in the convection pass. This position holds three O₂ sensors of the type ABB Zirconia Oxygen Analyzers AZ20. The emission monitoring in the CFB boiler is carried out in the stack position and is managed using the UV DOAS (AR600) and IR DOAS (AR650) analysis instrument from Opsis. The following gas components are normally quantified:

- Nitrogen oxides by measurement of nitrogen monoxide (NO), nitrogen dioxide (NO₂) and nitrous oxide (N₂O)
- Ammonia-slip (NH₃), i.e. excess ammonia after reduction of nitrogen oxides
- Sulfur dioxide (SO₂)
- Hydrochloric acid (HCl)
- Water (H₂O)
- Carbon monoxide (CO)
- Hydrogen fluoride (HF)
- Total organic carbon (TOC)

2.2 Experimental start-up and proceedings

Prior to the campaign start and the first delivery of ilmenite (Norwegian rock ilmenite, supplied by Titania A/S), the silo was nearly emptied of sand to minimize contamination of the fresh ilmenite. The small first portion of ilmenite (1.7 t) was then fed to the silo and from there to the furnace to ensure the system's capacity to handle the heavier material (bulk density: ilmenite $\approx$ 2 300 kg/m³, silica-sand $\approx$ 1 500 kg/m³). No problems related to external and internal feeding systems were detected. The remaining 30 t of the first delivery of ilmenite was then sent to the silo. Next, the feeding of fresh bed material as well as the return of used bed material via the drum sieve was stopped, while extraction of old bed sand continued. When the differential pressure across the bottom bed was reduced from 4 kPa to 3 kPa, feeding of fresh ilmenite was started. In this way, the ilmenite concentration in the furnace could be increased more quickly. As the bed pressure again reached 4 kPa, the feeding rate of fresh ilmenite was set to 15 t/d.

To achieve a fast increase of the ilmenite content in the boiler, it was chosen to increase the feed rate to 25 t/d during the second day. On the third day, the feed rate was set to 15 t/d, where it was kept for about two weeks followed by three days at 8 t/d, two days at 4 t/d and finally a little more than four days at 2 t/d. During the transition back to silica-sand operation, the feed rate was set to the nominal value for silica-sand operation, i.e. 8 t/d.

The first part of the experiment was dedicated to ensuring that the boiler system was able to handle the denser material, such as: pneumatic transport of the fresh material and fly ash, smooth operation of the bottom ash screw feeders and mechanical sieve for bed material recycling etc.

During the second part of the experiment, the surplus of air was lowered stepwise until the average oxygen concentration in the flue gases in the horizontal pass was as low as 1.8 vol.% (oxygen concentration during operation with silica-sand was usually 2.5-3.0 vol.%). Additionally, the thermal load was increased, and the recirculation of flue gases was stopped to achieve higher temperatures in the furnace.

2.3 Bed material sampling and ilmenite concentration

Bed ash samples were collected about three times per day. The samples were collected after the water-cooled bed ash extraction screw-feeders. Each sample was sieved, where the fraction $<710\ \mu\text{m}$ was used for further analysis and the fraction $>710\ \mu\text{m}$ (e.g. nails, small stones, hinges, etc.) was discarded. The ilmenite fraction in the samples $<710\ \mu\text{m}$ was then estimated by means of a rare earth roll belt magnet, see Figure 1. This magnetic separation system has a capacity of approximately 700 kg/h and consists of a belt stretched across two horizontal cylinders [9]. The left cylinder, see Figure 1a, comprises an electric motor, and the right cylinder comprises four sections of powerful neodymium magnets. The sample was fed evenly to the belt by means of a distributor, see Figure 1b. Non-magnetic material described a trajectory parabola to the front of the separator, while the magnetic material followed the belt around the magnetic drum and fell from the belt behind the magnet accordingly to Figure 1a.

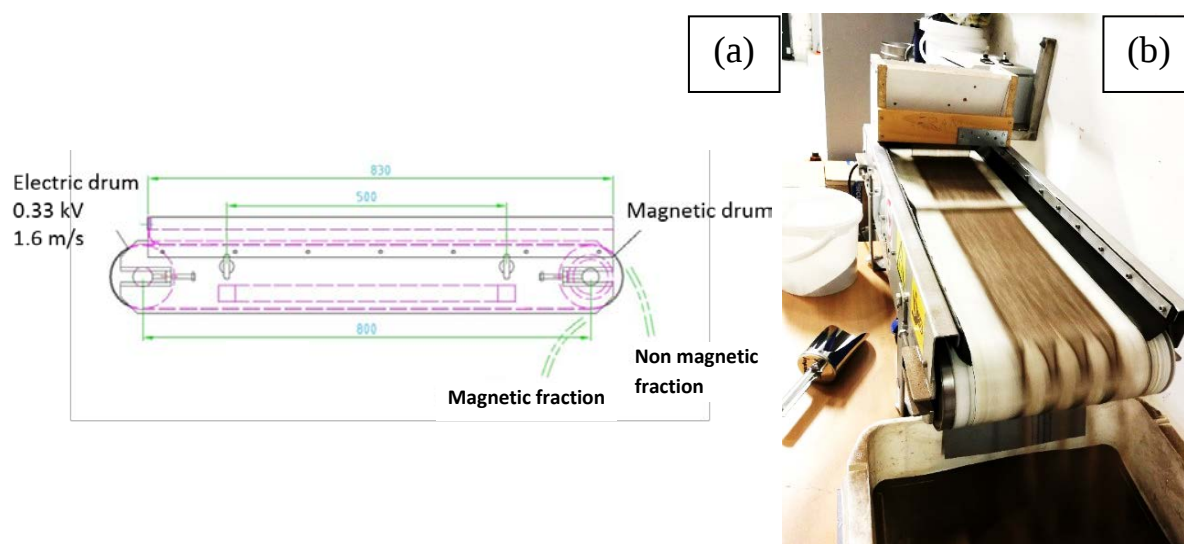


Figure 1: Schematic drawing of magnet separator (a), magnetic separator used in the experiments (b).

3 Results

The measured magnetic content in the bed ash samples ($<710\ \mu\text{m}$), together with the feeding rate of fresh ilmenite, is shown in Figure 2. The highest concentration of ilmenite was reached at roughly 300 h of operation and was about 90 wt.%, where the balance consisted mainly of fuel ash elements. The average fraction of discarded material ($>710\ \mu\text{m}$) was about 6 wt.% of

the total sample. The magnetic content increases most rapidly during the first 130 h, as a significant portion of the silica-sand bed was removed and replaced with ilmenite. After about 160 h, the magnetic fraction decreases, which is likely linked to an unwanted boiler stop due to external fuel problems, which caused a large part of the existing bed material to be replaced with fresh ilmenite (the magnetic properties of ilmenite are believed to vary over its lifetime, see below). An interesting observation is that while the feeding rate of fresh ilmenite is reduced from 15 t/d to 8 t/d, i.e. after about 220 h of operation, the magnetic fraction in the bed ash continued to increase. This observation can also be made when the feed rate is further reduced from 8 t/d to 4 t/d to 2 t/d (corresponds to approximately 0.72 kg/MWh). These observations are likely linked to a change in the magnetic susceptibility of the ilmenite particles, i.e. the degree of attraction a particle exhibits when exposed to a magnetic field. That is, magnetic susceptibility of the ilmenite particles increases with increased residence time in the system. Hence, the magnetic fraction of the bed ash measured during the initial part of the test campaign is believed to indicate values that are lower than the fraction of ilmenite. However, with increased residence time of the ilmenite in the boiler, magnetic fraction and ilmenite fraction become more congruent. Several research groups have previously shown that the physio-chemical properties of ilmenite particles change when subjected to continuous redox reactions, e.g. the iron in the particles migrates towards the particle surface [10,11], particle porosity increases [12] and particle density decreases. The driving force for these transformations is likely to be attributed to the varying partial pressure of oxygen surrounding the particle in the furnace as well as the higher diffusion rate of the iron fraction in the mixed oxide as compared to the titanium fraction. In summary, it is believed that the ilmenite fraction was higher than the (measured) magnetic fraction during approximately the first two thirds of the test period, when a significant portion of the ilmenite could not be separated magnetically. This observation should be more thoroughly investigated.

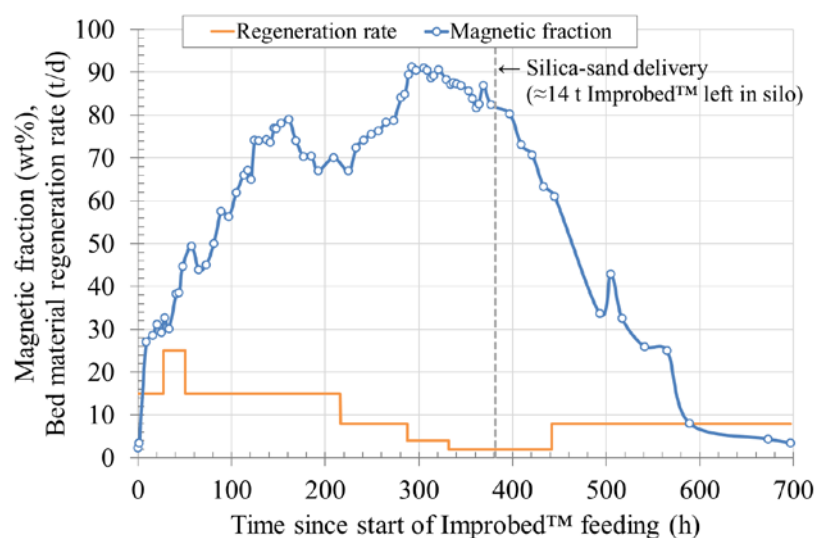


Figure 2: Measured magnetic fraction in the bed ash and feeding rate of fresh ilmenite to the furnace.

One of the greatest benefits of introducing an oxygen-active bed material in a CFB boiler is the possibility to even out the spatio-temporal distribution of oxygen in the furnace. Figure 3 shows hourly averages of the O₂ wet-gas fraction in the horizontal pass as well as dry- and wet-gas fractions in the stack as a function of the net boiler load. The net boiler load (i.e. not

including the flue gas condenser) could be increased from the nominal (i.e. maximum) boiler load of 115 MW to achieve continuous operation at about 123 MW, which corresponds to an increase of about 7 %. Further, Figure 3 confirms that the boiler could be operated continuously with an oxygen surplus in the flue gases as low as 1.8 vol.% for a significant time period without exceeding the maximum CO emission allowances. This can be compared to the wet-gas oxygen fraction in the horizontal pass during normal operation with silica-sand, which is usually set to 2.5-3.0 vol.% to ensure sufficient burnout of the fuel.

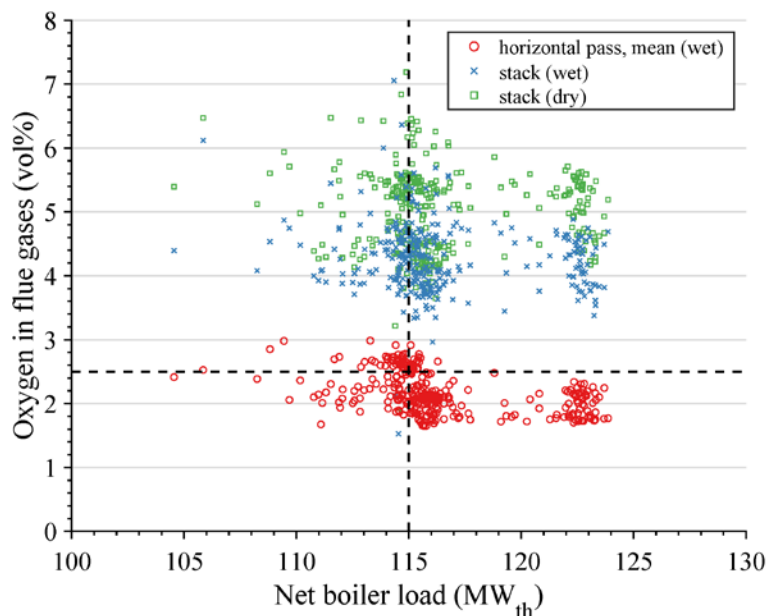


Figure 3: O_2 fraction during ilmenite operation in the horizontal pass for moist gas and O_2 fractions in the stack for dry and wet gas as a function of the net boiler load (dashed lines symbolizes set points for normal silica-sand operation, i.e. average O_2 and average net boiler load).

Figure 4 shows the total volume flow of gas fed to the furnace as primary air, secondary air, and recirculated flue gas as a function of the net boiler load during operation with ilmenite and silica-sand. During ilmenite operation, the total gas flow could be decreased significantly in comparison to silica-sand operation. In fact, during the highest continuous boiler operation with ilmenite, i.e. around 123 MW, the total gas flow through the system is lower than during silica-sand operation at 115 MW. The reason for this is the improved oxygen distribution in the furnace when applying OCAC, i.e. the air surplus can be lowered and thereby also the total airflow to the boiler. Another positive aspect of ilmenite operation in comparison to silica-sand operation is the possibility to reduce the amount of recirculated flue gas for the control of the bed temperature. The flue gas recirculation to the furnace was turned off during most of the operation with ilmenite, which decreased the volume flow of gas even further. This is possible as ilmenite is more robust with respect to agglomeration and sintering as compared to silica-sand; ilmenite has a higher melting point than silica-sand and alkali components are absorbed within the particles instead of on their surface as is the case with silica-sand [13], which ultimately allows higher operation temperatures. As can be seen in Figure 4, the total gas flow during ilmenite operation at a boiler load of 123 MW is approximately the same as during silica-sand operation at 113 MW. Consequently, the boiler can be operated in overload mode without increasing the gas velocity in the boiler and the convection path and without increasing the load on the textile filter and the flue gas fan.

Hence, the absolute wear of the boiler and filters should not change significantly, whereas the maintenance cost per MWh produced are reduced. The long-term effects of reduced gas flow and the change in alkali interaction are potentials that deserve further investigation, not least from a perspective of lowering maintenance costs.

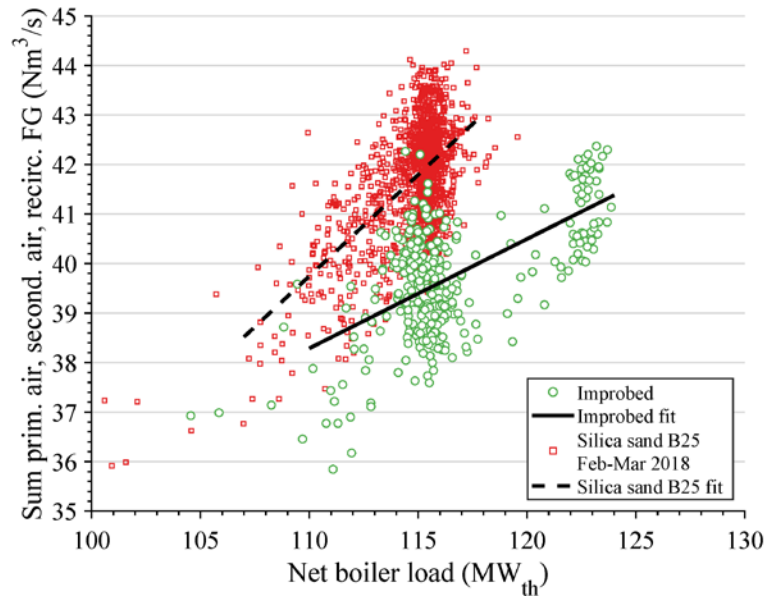


Figure 4: Total volume flow of gas fed to the furnace as primary air, secondary air, and recirculated flue gas as a function of the net boiler load during operation with ilmenite and silica-sand.

Figure 5 shows mean temperatures during ilmenite operation at four different heights in the furnace and in the horizontal pass as a function of the net boiler load. The average bed temperature at 115 MW is about the same as at 123 MW, whereas the furnace temperatures at 8.5 m and 13.5 m above the fluidization nozzles seem to increase with increasing net boiler load.

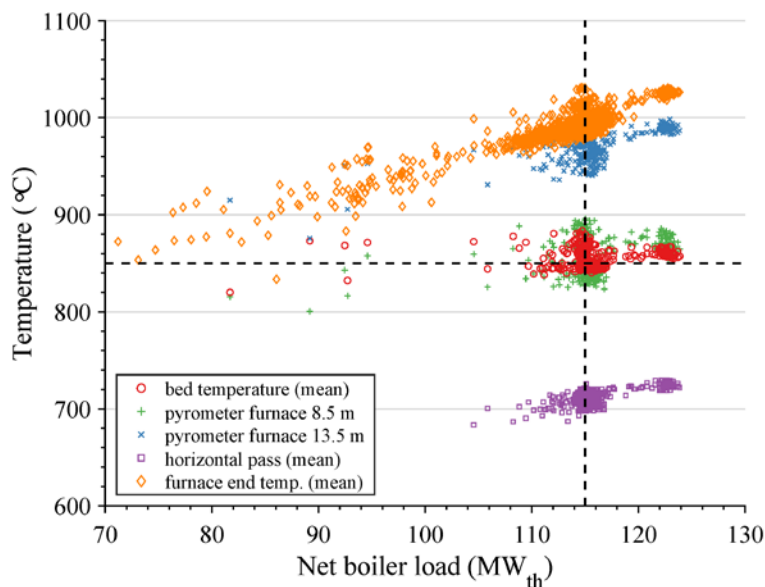


Figure 5: Mean temperatures during ilmenite operation at four different heights in the furnace and in the horizontal pass as a function of net boiler load (dashed lines symbolize set points for silica-sand operation, i.e. nominal bed temperature and nominal net boiler load).

Figure 6 shows the concentration of NO_x in the stack position measured as mg/Nm³ dry-gas at 6 vol.% O₂ as a function of the furnace end temperature on hourly average. All NO_x values during ilmenite operation were clearly below the maximum allowed daily average (275 mg/Nm³ at 6 vol.% O₂) and the highest values of ammonia emissions were below 2 mg/Nm³ at 6 vol.% O₂ (not shown in the figure). During one weekend, the ammonia tank reached a low level, which resulted in insufficient regulation of ammonia injection to the furnace and, hence, to high NO_x values (>100 mg/Nm³ at 6 vol.% O₂). The highest furnace end temperatures, i.e. 1025 °C, occurred when the boiler was operated at 123 MW without flue gas recirculation, which initially lead to elevated NO_x emissions (>100 mg/Nm³ at 6 vol.% O₂) for about three hours.

For temperatures below 1000 °C, it seems that the NO_x emissions during ilmenite operation were slightly higher than the corresponding silica-sand emissions. Above 1000 °C there is no reference data for silica-sand operation, and NO_x emissions for ilmenite operation are as low as emissions for silica-sand operation at 975-1000 °C. In general, ammonia injection during ilmenite operation was higher compared to silica-sand operation (in average 38 % higher at a furnace end temperature of 1000 °C).

An interesting observation is the trend of NO_x emissions, where the concentration decreases with increased temperature in the furnace. This may seem contrary to the experience that higher temperatures produce higher NO_x, but this is likely linked to interacting mechanisms: a lower air surplus, i.e. a lower local partial pressure of oxygen in the furnace, is known to reduce the formation of NO_x. Further, a lower air surplus usually causes the CO to increase locally, which in turn reduces NO_x and decreases emissions of nitrogen oxide.

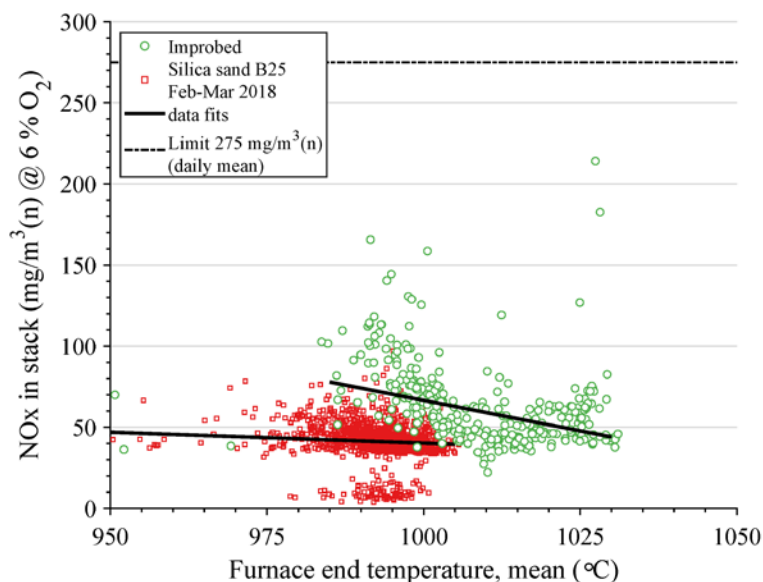


Figure 6: NO_x concentration in the stack measured as mg/Nm³ dry-gas at 6 vol.% O₂ as a function of the furnace end temperature on hourly basis

4 Conclusions

Three weeks of full-scale operation have been achieved, where the oxygen-carrier ilmenite (FeTiO₃) has been used as bed material in a biomass-fired 115 MW_{th} CFB-boiler. The

experiments show that (1) it is possible to change bed material from silica-sand to ilmenite without making changes to existing equipment and (2) that the external and internal bed material logistics works equally well. Ilmenite improves the oxygen distribution in the furnace, which enabled a reduction of the air surplus by as much as 30 % and an increase of the net boiler load from 115 MW_{th} to 123 MW_{th}. The experiment show that average NO_x concentrations and ammonia consumption tend to be higher as compared to silica-sand operation.

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