NOx reduction and efficiency improvement of a 210 MW_t coal-fired boiler co-firing biomass

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Abstract:

Until 2016 in the European Union, the permitted NOx emission concentration for power plants of between 50 and 500 MW_t was 600 mg/Nm^3. From 2016 to 2020 the NOx emissions for power plants of 300 to 500 MW_t must be decreased to below the limit of 200 mg/Nm^3. The new limit represents a considerable challenge. In this paper, we present the results of several measures for NOx reduction and efficiency improvement, performed on a 210 MW_t coal-fired boiler that co-fires biomass. The goal of the project was to reduce NOx emissions by 20 to 30% on average over the boiler's operational range. To meet the goal, the boiler's configuration and operation were analysed in order to find potential issues and to propose improvements. In this regard, several measures, such as the installation of an electrostatic discharge measuring system, relocation of over-fire air, upgrade of fuel delivery system, application of secondary air at inactive burners and application of advanced combustion control solution, were conducted, significantly improving the boiler's performance. The project goal related to NOx emissions was met and exceeded, and the efficiency of the boiler was significantly improved.

Keywords:

Coal-fired Boiler, NOx Reduction, Efficiency Improvement, Combustion Optimization, Fuel Delivery System, Emission Measurements, Model Predictive Control

1. Introduction

With regard to environmental care, the European Union (EU) introduced new exhaust gas regulations [1], which specified new limitations on harmful emissions by exhaust gasses from larger energy systems. The new limitations had to be reached by 2016. Table 1 shows the permissible limitations from main propulsion installations (for combustion plants using solid or liquid fuels with the exception of gas turbines and gas engines) before 1.1.2016 and after 1.1.2016.

Table 1. The permitted values of main propulsion installations before 1.1.2016 and after 1.1.2016.

Parameter	Expressed as	Unit	Until 1.1.2016	After 1.1.2016 (in case of not accepted TNP*)
Total dust	-	mg/m^3	100	20
Sulphur oxides SOx	SO_2	mg/m^3	476	200
Nitrogen oxides NOx	NO_2	mg/m^3	600	200
Carbon monoxide	CO	mg/m^3	250	-

*TNP: Transitional National Plan according to Article 32, IED Directives [1].

Before 2016, the permitted limitation for nitrogen oxides (NOx) was 600 mg/m^3, for carbon monoxide (CO) 250 mg/m^3 (this limitation is imposed by Slovenian law; it is not prescribed by the IED Directives [1]), for sulphur oxides (SOx) 476 mg/m^3 and for total dust 100 mg/m^3; all values are calculated per 6% dry O_2 basis. Sulphur oxides and total dust are not a big issue for power plants that burn good-quality coal. On the other hand, NOx emissions represent a rather major issue in the majority of existing power plants, as their limit was radically reduced from 600 mg/m^3 to 200 mg/m^3. However, time to comply with the new limitations has been somewhat alleviated for those power plants that applied for the Transitional National Plan, according to Article 32 [1].

Combustion in industrial boilers is a rather complex process, which is influenced by many factors. The plant's secondary control, variable production of heat and steam for district heating and nearby industry, can significantly impact the control of plants and hence the combustion in boilers. Factors such as coal quality, its water content, degradation of mills, etc. additionally influence combustion and hence the boiler's emissions and its efficiency.

Many studies can be found on the reduction of NOx emissions, in which approaches are divided into primary and secondary measures. Primary measures relate directly to the combustion itself, for which several procedures to reduce NOx emissions have been proposed [2]. Secondary measures relate to post combustion with exhaust gas treatment technologies. The secondary measures are out of the scope of this paper and thus more focus is given to the primary measures.

Low-NOx burner technologies [3, 4] have been around for couple of decades and can be provided by all major players in the market. Over-fire air (OFA) or air staging [5-7] is commonly described as the introduction of over-fire air into the boiler or furnace. Staging the air in the burner (internal air staging) is generally one of the design features of low-NOx burners. Fuel staging is also a known technique for NOx reduction, where several approaches such as burner out of service (boos) [8], fuel biasing [8] and reburning [9] can be applied. Exhaust gas recirculation [10, 11] for NOx control includes gas recirculation into the furnace or into the burner. In this technology, 20-30% of the exhaust gas (at 350-400°C) is re-circulated and mixed with the combustion air. Furthermore, excess air control or burner fine tuning is usually one of the first methods used to control the NOx formation. Among advanced combustion control techniques, model predictive control technology [12] has been widely accepted. Due not only to fuel staging with biomass, but also to the fact that biomass contains less fuel-bound nitrogen, biomass co-firing also represents a means for NOx reduction [13]. Formation of NOx emissions in industrial boilers has also been a focus of many modelling studies [14-16].

In this paper, measures for NOx reduction and efficiency improvement applied on a 210 MW_t coal-fired boiler that co-fires biomass are presented. The goal of the project was to reduce NOx emissions by 20 to 30%. To achieve the goal, the boiler's configurations, components and operation were scrutinized, and bottlenecks were identified. Furthermore, several measures such as the upgrading of the measuring system for exhaust gas emissions, installation of Electrostatic Discharge (ESD) measurements, upgrading of the fuel delivery system, relocation of over-fire air, modification and retuning of the primary control system, application of secondary air at inactive burners and installation of an advanced combustion control solution were proposed and realized between 2012 and 2014. Significantly reduced NOx emissions and increased boiler efficiency are reported in terms of “before and after” results.

2. Boiler description

The schematic diagram of the boiler is shown in Fig. 1. The boiler is a 210 MW_t water-tube, radiant, single-drum type with natural circulation. It is a brown coal-fired boiler modified to co-fire biomass (wooden chips) up to 25% of its maximum power. The brown coal flows through four mills, where it is pulverized and then fired by low-NOx burners, which are installed above the biomass firing system. Two or three mills are in operation at the same time, while one or two are in reserve. The boiler's nominal operating point is at 75 kg/s of fresh steam, with a temperature of 535°C and a pressure of 95 bars. The lower calorific value (LHV) of coal can vary from 17 to 19 MJ/kg, whereas the LHV of the biomass can vary from 10 to 12 MJ/kg. Primary air, of which mass flow is constant, is mixed with the pulverized coal and fired into the boiler's furnace. Secondary air is injected through the outer tube of the burner and controlled in order to ensure the proper mixture of coal and combustion air. The biomass firing system is installed below the low-NOx burners; it consists of three separate air zones, i.e. biomass drying, burning and afterburning zones.

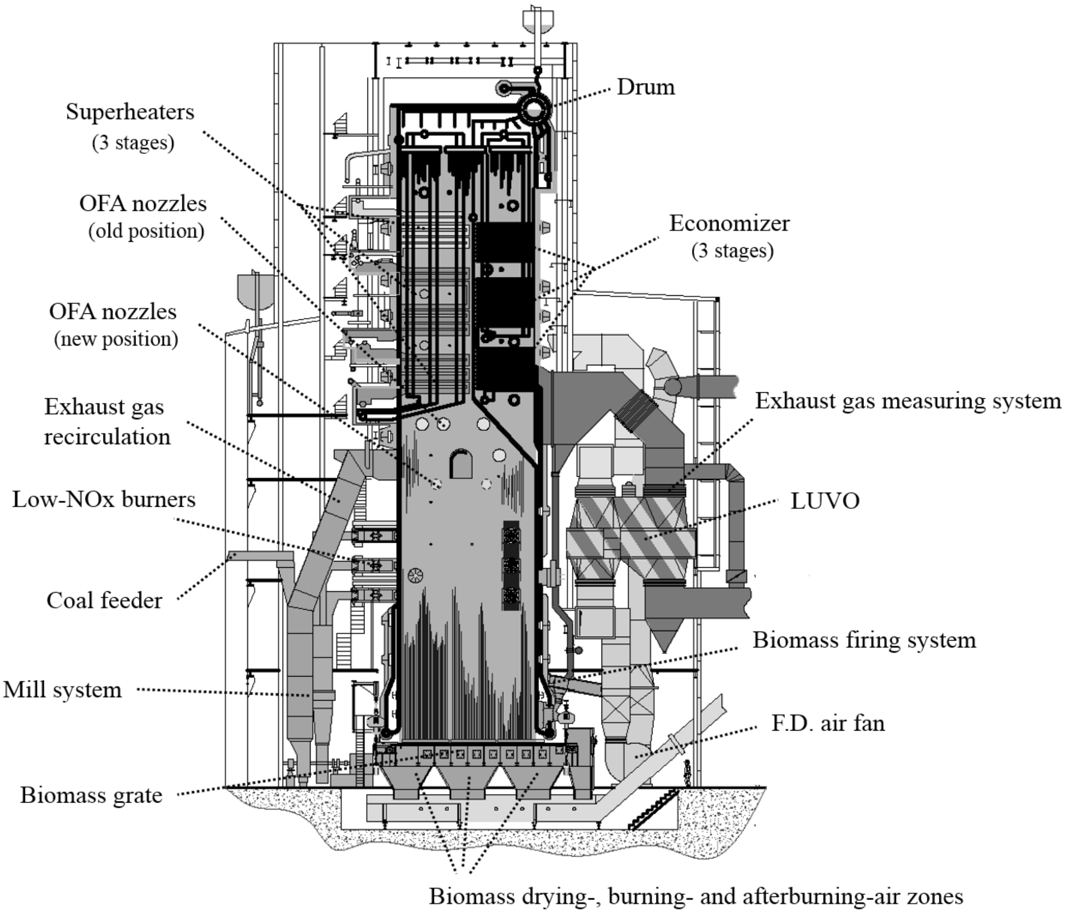

Fig. 1. Schematic representation of the boiler.

The boiler uses over-fire air (OFA) in order to complete the combustion of unburned hydrocarbons. Exhaust gases, which are a product of combustion, flow through the furnace and pass the OFA zone, which consists of eight OFA nozzles divided into two sectors that are found on the left and right sides of the boiler. Each side of the OFA mass flows is controlled separately. After the OFA zone, the exhaust gases pass across the three consecutive superheaters of fresh steam, where they change direction (see Fig. 1) and flow through the pipes of the economizer, where the water is brought to boiling point. In the last stage, the exhaust gases flow through the heat exchanger for combustion air pre-heating (LUVO), before which system for measuring emissions is installed. The air pre-heating is carried out by two parallel rotating regenerative single-pass air heaters, and sack filters are used for exhaust gas cleaning.

3. NOx emissions and efficiency

NOx reduction techniques are quite complementary with efficiency improvement techniques, from the operational point of view. In the following, the NOx reduction and efficiency improvement mechanisms are discussed.

3.1 NOx emissions

NOx formation mechanisms

The formation of NOx emissions in a specific combustion device is determined by an interaction of chemical and physical processes that occur within a furnace. The three principal formations of NOx emissions are "thermal" NOx, "prompt" NOx, and "fuel" NOx [17-19]. In coal-fired boilers, the majority of NOx emissions are represented by the fuel and thermal NOx. However, the relative contribution of each to the total NOx formed depends on the combustion process and fuel characteristics. The thermal NOx is formed due to oxidation of the molecular nitrogen in combustion air at high temperatures; it represents up to 20% of the total formed NOx emissions in pulverized boilers. The fuel NOx results from oxidation of chemically bound nitrogen in the fuel and represents the majority, i.e. up to 80% of the total amount of NOx emissions in pulverized boilers. Prompt NOx results from the reaction between nitrogen and hydrocarbon radicals and represents only a fraction of the total amount of NOx emissions in coal-fired boilers.

NOx control mechanisms

Technologies for NOx reduction can be grouped into primary and secondary control technologies. Primary control technologies reduce the amount of NOx produced in the primary combustion zone. Secondary control technologies reduce the NOx present in the exhaust gas away from the primary combustion zone.

Among primary control technologies, most popular and also effective are the application of low-NOx burners (LNB) and the use of over-fire air (OFA). The LNB reduces NOx formation by controlling the stoichiometric and temperature profiles of the combustion process [20, 21]. This control is achieved by regulating the distribution and mixing of the fuel and air, thereby yielding one or more of the following conditions: (1) reduced O_2 in the primary flame zone, which limits both thermal and fuel NOx formation; (2) reduced flame temperature, which limits thermal NOx formation; and (3) reduced residence time at peak temperature, which limits thermal NOx formation.

The OFA (also referred to as air staging) is a combustion control technology, in which a fraction, 5–20%, of the total combustion air is diverted from the burners and injected through nozzles located above the top burner level [20, 21]. The OFA is used in conjunction with operating the burners at a lower-than-normal air-to-fuel ratio, which reduces NOx formation. The OFA is then added to achieve complete combustion. The OFA can be used in conjunction with LNBs. The addition of OFA to LNB on wall-fired boilers may increase the reduction of NOx emissions by an additional 10–25%.

Other NOx control mechanisms are fuel staging or reburning [22, 23], exhaust gas recirculation and burner optimization for NOx control [2].

Popular among secondary control mechanisms are selective noncatalytic reduction (SNCR) [24, 25], and selective catalytic reduction (SCR) [23, 26]. As the project frame considered only primary measures for NOx control, the secondary control mechanisms are not addressed in more detail in this paper.

3.2 Efficiency

A boiler is a steam-generating device, which produces steam by the burning of fuel. If the fuel has a higher LHV in general, then it is able to produce more heat per kg of fuel, which is directly proportional to the efficiency [27]. The boiler’s efficiency can be determined based on direct [28] or indirect [28, 29] methods. Each method has its own advantages and disadvantages. The direct method yields more realistic efficiency values. On the other hand, in order to understand where the major losses are located, the indirect method is more appropriate. In this boiler, the efficiency was determined based on the indirect method, where losses were measured [30] directly except for radiation and convection losses, which are estimated according to the standard procedure [29]. The losses can be divided into four major groups according to the following equation:

$$\eta = 100 - (L_1 + L_2 + L_3 + L_4)$$

where,

L_1 - Losses due to dry exhaust gas

L_2 - Losses due to water content in fuel and air

L_3 - Radiation and convection heat losses

L_4 - Unburnt loss

Before the implemented modifications and upgrades, the boiler suffered the following losses: the stack losses represented about 8% ($L_1 + L_2$), the radiation and convection heat losses represented about 1.1% and the losses due to unburned compounds represented about 2%. From the above, it can be seen that the exhaust-gas losses were the highest and significantly affected the boiler's efficiency.

4. NOx emissions reduction and efficiency improvement of the boiler

From the boiler's description in Section 2, it can be seen that the boiler already employed several primary measures for NOx reduction, i.e. low-NOx burners, over-fire air and exhaust gas recirculation. The use of biomass (wooden chips) in the boiler also reduces NOx emissions. This is due to the lower fuel-bound nitrogen concentration in biomass, which is fired up to 25% of maximum thermal load, and due to the staging of fuel, where biomass is fired on the grate in the hopper of the boiler. The result is the reduction in fuel- and thermal-NOx emissions, respectively. On the other hand, biomass reduces the boiler's efficiency from 1 to 2.5% (depending on the boiler's load and the amount of biomass) because of the higher water content in the biomass [30]. Nevertheless, the use of biomass is still welcome due to the reduction of CO_2 emissions from the coal side.

From Section 3 we can derive some common points for NOx reduction and efficiency improvement techniques. Excess air increases NOx emissions and decreases the boiler's efficiency due to the gas losses through the stack; these represent the major losses. Air distribution and its ratio between the low-NOx burners and the OFA are also important, from NOx and efficiency perspectives.

By analysing combustion-related segments of the boiler, such as the measuring system of emissions, fuel delivery system, mills, coal and biomass combustion systems and combustion air flows, it was discovered that there is significant potential for improvements to the boiler. After identifying the major issues, the following measures were taken:

- Upgrading to 8-point-based measuring system of exhaust gas emissions
- Installation of ESD measuring system to determine distribution and velocity of pulverized coal particles
- Modification of fuel delivery system
- Application of secondary air at inactive burners
- Relocation of OFA nozzles
- Modifications and retuning of primary controls
- Application of Advanced Combustion Control (ACC) solution based on Model Predictive Control (MPC) technology

In the following, each of the above-mentioned measures is briefly described.

4.1 Upgrade to the 8-point-based measuring system of exhaust gas emissions

The boiler has a specific design as can be seen in Fig. 1. The schematic shows that the boiler exhaust gas duct system turns downwards after the first stage of superheaters and thus has a relatively short furnace. Regarding the optimization of combustion, the best practice is to measure the exhaust gas emissions and its temperature in the location between radiant and convective heat exchangers [31]. The advantage of such a type of measuring system is that it is installed practically above the combustion zone and thus provides direct information on combustion. Also, it ensures short dead times between fuel and air delivery systems and exhaust gas emission measurements, which is desirable from the boiler's control aspects.

An inspection of the boiler revealed that, due to the downward bend of the exhaust gas duct system, the installation of such a type of measuring system is not possible in practice. Hence, it was decided that the measuring system will remain at the original location, which is before the exhaust-gas-to-air heat exchanger (LUVO). The location is rather distant from the combustion zone, but it still enables significant improvements in the combustion via the ACC solution, which considers the system's dead times in its calculations.

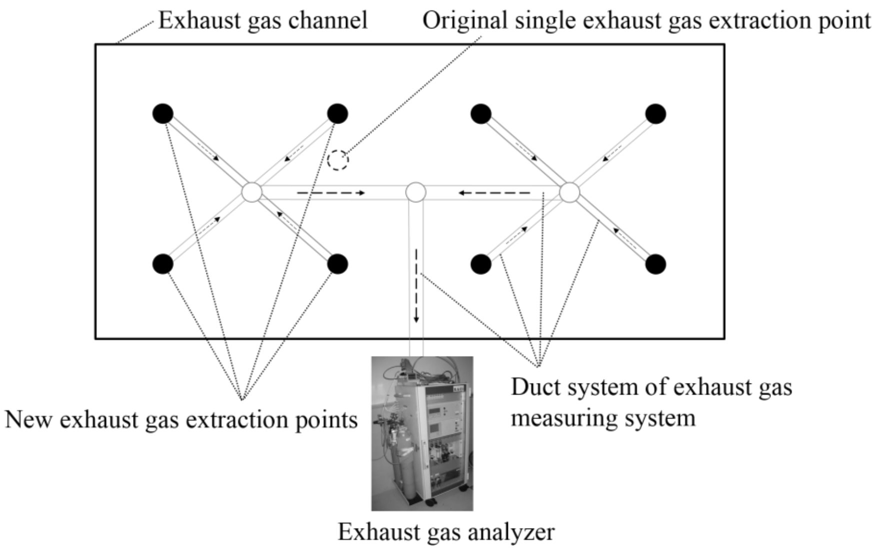

Fig. 2. Schematic representation of the 8-point-based measuring system of exhaust gas emissions.

Within the scope of the boiler's combustion optimization, a significant modification of the measuring system of exhaust gas emissions was then performed. The original 1-point-based measuring system (indicated by the circular dashed line) was replaced by an 8-point-based measuring system, which are represented by the schematic in Fig. 2. The measurement of the new net measuring system represents average values of exhaust gas emissions extracted over the cross section of the exhaust-gas channel. The comparison between 1- and 8-point-based measuring systems clearly showed that the 8-point-based measuring system provides much more consistent and reliable values of exhaust gas emission concentrations. The difference is noticeable at transients, especially at changes of coal and biomass loads. Due to the fact that the optimization of the combustion is directly related to the exhaust gas emissions, the net measuring system represents a significantly better and more reliable basis for the commissioning of the ACC solution, described later in the paper.

4.2 Installation of the ESD measuring system

Every burner in the boiler consists of three nozzles; through the central part of each flows a mixture of primary air and pulverized coal, and through the outer tube flows the secondary air. Due to the changing quality of the coal and the mills' grinding, deviations were constantly present in the distribution of pulverized coal through the combustion duct system and the three combustion nozzles. Since the flow of the secondary air through each of the three nozzles was equal, the ratios between the mass flow of fuel and the mass flow of secondary air were different in each of the three nozzles. The consequence was a non-optimal mixture between fuel and air, which resulted in additional CO and NOx emissions and increased unburnt compounds.

In order to improve the mixture of fuel and combustion air at the burner level, an Electrostatic Discharge (ESD) measuring system [32] was installed in the pulverized coal duct system, as represented in Fig. 3.

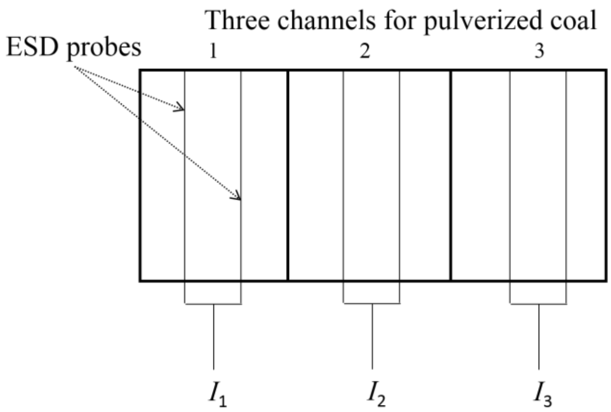

Fig. 3. Schematic representation of the ESD measuring system.

Fig. 3 shows the three channels, in the pulverized coal firing system, which lead to each burner nozzle. The ESD system determines the distribution and velocity of the pulverized coal particles, based on which a proper distribution of the secondary air through the three nozzles is achieved. As shown in the figure, each channel has two probes, across which the pulverized coal particles flow and generate the electrostatic discharges, I_i. The discharges are used to determine the amount of pulverized coal in each channel and to properly adjust the mass flows of the secondary air in each channel. The air hatches are controlled in such a way that the constant fuel-to-air mass flow ratios in all three burner nozzles are ensured. By introducing the ESD measuring system, a higher quality of mixing was established, which resulted in higher combustion stability and efficiency and lower exhaust gas emissions.

4.3 Modification of the fuel delivery system

Good operation of the fuel delivery system is important as it has to continuously deliver the correct amount of coal by conveyor belts. The issue in the boiler was related to the too large distances between the crossbars on the conveyor belts. Because the distances were too large, unequal amounts of coal were piling up at crossbars during the transportation, as shown in the left-side schematic in Fig. 4. This caused non-continuous mass flow of coal into the mills and hence to the burners. The consequences were reflected in CO emissions and in rather dynamic control of the air hatches, which are controlled based on the ESD measuring system, described in the previous section.

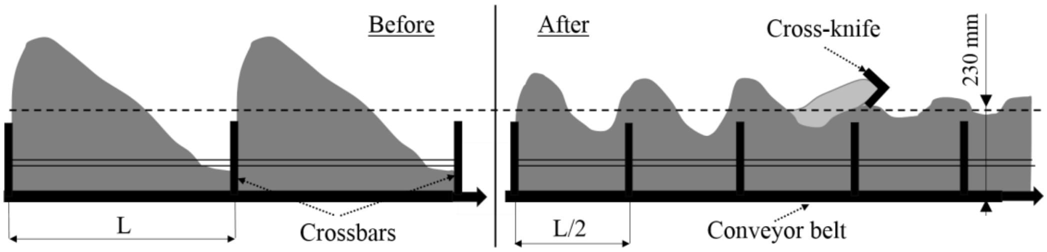

Fig. 4. Distribution of coal between crossbars before and after the upgrades.

The problem was solved by modifying the coal delivery system; additional crossbars were installed at half distances between the original crossbar positions, as indicated by the right-side schematic in Fig. 4. Moreover, a cross-knife for coal levelling and the mills' tables were properly upgraded as well. The results were seen in the improved grinding of mills, more continuous pulverized coal flow to the burners and lower dynamic of burner air hatches. The upgrades did not affect the NOx emissions directly, but by ensuring better quality of the coal delivery system, a sound basis was provided for stable and more rigorous combustion under reduced oxygen levels in the furnace, enabling significant reduction of the NOx emissions by the ACC solution.

4.4 Application of the secondary air at inactive burners

Air for the combustion of pulverized coal in low-NOx burners is divided into primary and secondary air. In the past, the primary air was also applied for mills' cooling in the boiler, but nowadays the role of mills' cooling has been replaced by applying recirculated exhaust gases. Also, due to primary measures, the primary air was minimized, which significantly improved thermal NOx emissions.

During boiler operation, for 80% of the time, only two out of four burners are active. Such operation is used for up to about 85% of the boiler's load (depending on the amount of biomass co-firing), whereas operation above 85% load requires additional burner, and operation with three burners must be conducted. This means that, 80% of the time, two burners are inactive and, 20% of the time, one burner is inactive.

Tests were carried out, in which we redistributed a part of the secondary air in the active burners to the secondary air of the inactive burners. Through this measure, a significant amount of air was taken away from the high-temperature zone of the active burners and added to the inactive burners in order to satisfy the boiler's stoichiometric requirements. As a consequence, a significant reduction in NOx emissions was observed. However, the effect of the application of the secondary air to the inactive burners on NOx emission reduction was decreased after relocating the OFA nozzles.

4.5 Relocation of the OFA nozzles

Based on test observations, it was noticed that the OFA nozzles were located too close to the superheaters in the boiler. Thus, the zone above the OFA was too short to complete the combustion, and excessive O_2 levels in the exhaust gas were recorded. Several options to improve the effect of OFA were considered. In the first measure, the OFA air was activated only in a specific range of the boiler's operation, otherwise the excess of O_2 in the exhaust gas was too high in the particular operational range, significantly reducing the boiler's efficiency. Then a major boiler modification was conducted; the OFA nozzles were relocated a few metres downwards, towards the burners, as schematically indicated in Fig. 1. Through the modification, there was a practical problem, as there were limited possibilities for the relocation of the whole OFA system. Nevertheless, the result of relocation was improved combustion and reduced excess air over most of the operational range of the boiler. However, the NOx emissions were slightly increased at higher loads. The reason was a smaller relative distance between the low-NOx burners and the OFA nozzles. With higher loads, the flame size, its temperature and the OFA flow increase, reducing the relative distance and establishing the necessary conditions for NOx emissions' generation.

4.6 Modifications and retuning of the primary controls

Due to the installation of the ESD measuring system, the application of secondary air at inactive burners and the modification of the fuel delivery system, major updates and controller tuning of the primary controls had to be conducted. In this regard, several step tests, related to each modification in order to retune or update the primary PI/PID control system, were performed. The primary control updates were performed iteratively and several times after the major boiler modifications, as they are interrelated, changing the combustion characteristics in the furnace. The modifications of the primary controls were of major importance in order to establish a good and concrete basis before installing the ACC technology, which is described in the following section.

4.7 Application of the Advanced Combustion Control

Combustion is a rather complex process; a mathematical description of exhaust gas emissions represents a highly nonlinear model. Moreover, the size of such boilers implies significant dead times between manipulated and controlled variables, which, through the system's nonlinear dynamics and input-output delays, represent a significant control challenge. These are known drawbacks of PI/PID controllers [33], which are still quite frequently used in combustion applications and can be solved by more complex supervisory-controller approaches.

The last part of the project thus included the installation and commissioning of an Advanced Combustion Control solution [34]. The solution is based on Model Predictive Control (MPC) technology [35], which uses a mathematical model of the boiler to predict its future behaviour and calculate its optimal control trajectory. In this regard, several persistent excitation tests were conducted in order to capture the boiler's characteristics. Based on the multi-input-multi-output model, applying the available boiler's measurements, the information about the combustion states are processed and predicted. By applying MPC technology that uses a cost function in conjunction with specific combustion constraints (multi-criteria optimization), the optimal settings of the boiler's manipulated variables are identified and fed back into the plant's DCS/PLC system.

Excess air control via burner and OFA fine tuning was conducted by applying the ACC solution. Optimal settings are continuously calculated in on-line mode, ensuring sustainable and efficient use of fuel and reduction of losses via heat of exhaust gases. In this way, a major reduction in NOx emissions and increase in boiler efficiency were achieved.

5. Results and discussion

5.1 Comparison of the NOx and O_2 emissions

Figure 5 shows the histograms of the NOx and O_2 emissions, boiler load and usage of biomass in the operation of the boiler from January to May 2012 (grey) and from January to May 2014 (black), representing "before and after" results with respect to the described modifications and upgrades. The average value of the boiler's load was around 70% in 2014 and around 75% in 2012. The higher representation of loads under 70% in 2014 is slightly disadvantageous, as increasingly more combustion air has to be added with lower loads in order to complete combustion, which, on other hand, increases the generation of NOx emissions. Conversely, the biomass usage was much higher in 2014 (the average value was around 47.5% of grain transport) than in 2012 (the average value was around 35% of grain transport). Biomass has less fuel-bound nitrogen and it represents a fuel staging thus further decreasing NOx emissions, which, as mentioned, was favourable in 2014. Since the average value of the load was favourable in 2012, the reduction in NOx emissions is compensated overall due to the higher usage of biomass in 2014. This ensures that the basis for comparison of the results is rather fair.

The results show that the NOx emissions were significantly improved, as illustrated by the histogram in Fig. 5. The average value of NOx emissions was 315 mg/m^3 in 2012, whereas it was 186 mg/m^3 in 2014, which represents about 40% reduction.

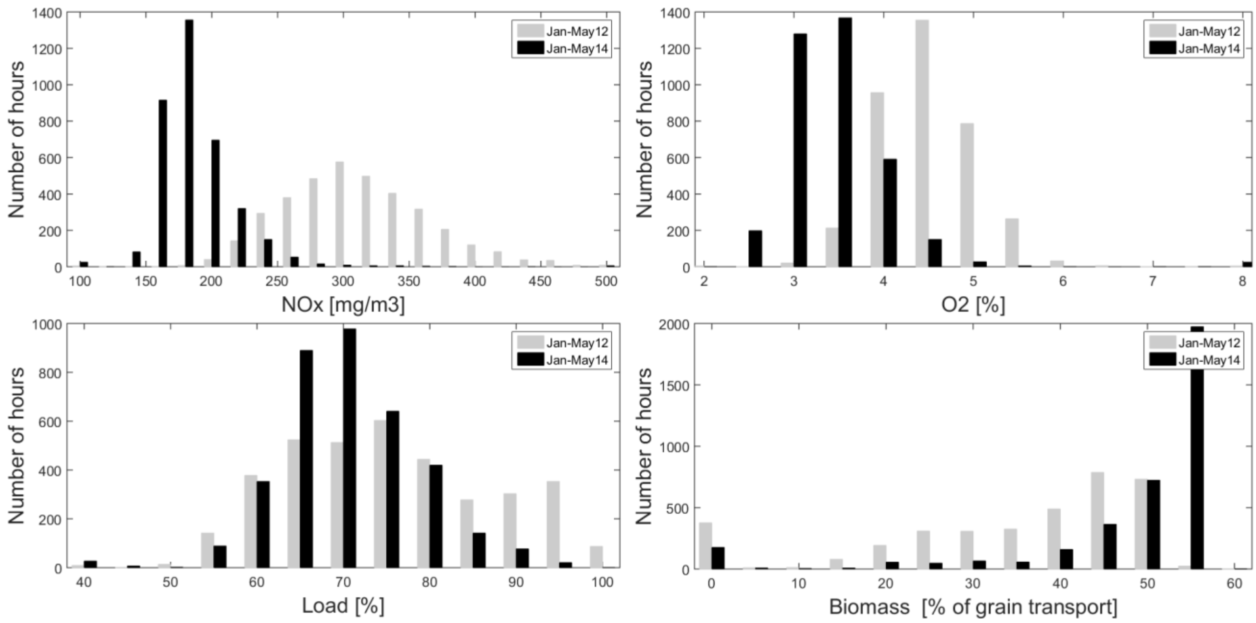

Fig. 5. Histograms of NOx and O_2 emissions, boiler load and usage of biomass from January to May 2012 (grey) and from January to May 2014 (black).

From the NOx histogram, it can be seen that the NOx emissions still exceeded the limit of 200 mg/m^3 in 2014. From the left-side graph in Fig. 6, which shows NOx emissions as a function of the boiler's load, it can be seen that, in 2014, the NOx emissions were on average above the limit of 200 mg/m^3 in the ranges below 61% and above 83% load. This is due to the boiler's characteristics; at lower loads more air has to be added in order to achieve complete combustion at the given volume of the boiler. Increasing generation of NOx emissions above 83% load is due to the small relative distance between the low-NOx burners and the OFA nozzles, as described in Section 4.5. Nevertheless, the results are dramatically better in comparison with 2012. From Fig. 5 we can observe that the average values of NOx emissions in 2012 were overall above 300 mg/m^3, whereas in 2014 they were mainly below 200 mg/m^3. Moreover, in 2014, the first standard deviations of NOx emissions, which are denoted by vertical lines, were significantly reduced in comparison with 2012. This can be attributed to the ACC solution that fine-tunes the fuel and air flows.

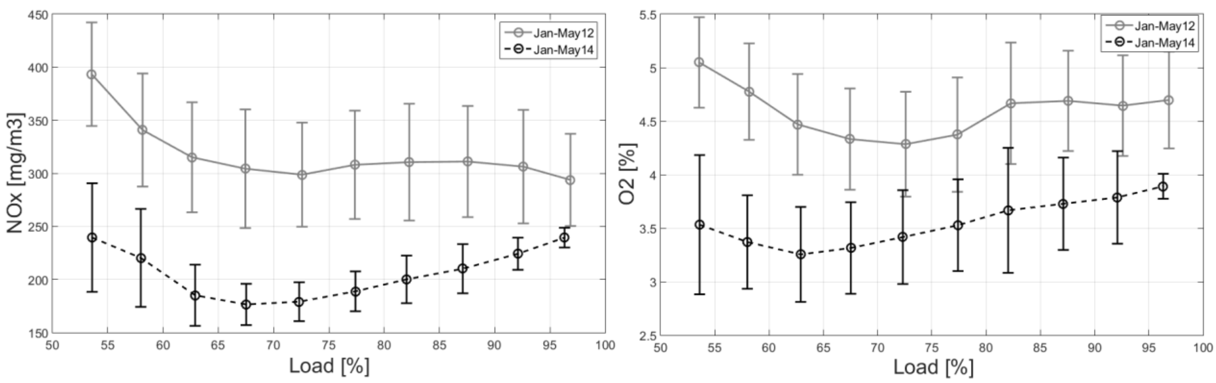

Fig. 6. NOx and O_2 emissions as a function of boiler load from January to May 2012 (grey) and from January to May 2014 (black).

The percentage of the O_2 was also significantly improved, as seen from the histogram in Fig. 5 and the right-side graph in Fig. 6, meaning that the losses of exhaust gases were reduced and higher efficiency of the boiler was achieved. The average value of the O_2 concentration was 4.51 mg/m^3 in 2012 and 3.49 mg/m^3 in 2014. Based on the O_2 difference, it was estimated that the decrease in the O_2 in exhaust gas increased the boiler's efficiency by 1.1%. However, the standard deviation of the O_2 remained practically unchanged. This can be mainly attributed to the combustion of the biomass, whose quality, and hence its combustion, is highly diverse, and to the excess air needed for the complete combustion of the biomass on the travelling grate.

Effects of modifications and upgrades

The above results show a reduction in the NOx emissions of about 40% on account of all the modifications and upgrades described in this paper. The contribution of each upgrade is hard to assess separately as they are strongly interrelated and upgrades and modifications were in most cases done iteratively. For instance, the installation of the ESD measuring system did not affect the NOx emissions directly, but with an ensured proper mixture of air-to-coal ratio on the burner levels, a more rigorous optimization of combustion and hence NOx emissions was achieved along with subsequent tests and control improvements. Moreover, the ESD probe system and its controls had to be re-examined, along with the fuel delivery system modifications and upgrades, and then again with OFA relocation and application of inactive secondary airs as the combustion characteristics in the boiler changed.

However, the authors attempted to make a thumb-rule assessment of the modifications and upgrades performed on the boiler. The ESD system installation, in tandem with the fuel delivery and corresponding control systems' upgrades, gave about 7-10% of the total 40% reduction in the NOx emissions. Relocation of the OFA system gave on average 10% and the application of the inactive secondary airs contributed up to about 5% of the 40% NOx emissions reduction. The ACC installation, applied after all the system modifications, resulted in about 15% of the total 40% reduction of the NOx emissions, as discussed in the next section.

5.2 Comparison of the boiler control with and without the ACC

After all the upgrades and modifications performed, as described in Section 4, the ACC solution was installed and commissioned. Figure 7 shows the first tests of the boiler with and without ACC control. The first graph represents NOx emissions where denotation 6 means that the emissions were normalized to 6% O_2, dry basis. On the graph, the 200 mg/m^3 NOx limit is denoted by a dashed line, representing the new EU regulation limit. The second graph represents O_2, with the line at 4% being drawn for easier orientation. The third graph shows the boiler's load and the percentage of biomass grain transport, where 55% of grain transport corresponds to 25% of the boiler's maximum power. From the graph, it can be noticed that the biomass was practically at maximum usage or close to it most of the time.

The test with and without the ACC solution comprised 54 hours of operation, during which every six hours the ACC was switched on and off. For easier comparison, the grey shaded area represents the time with ACC activated, whereas the white area represents the time without ACC being activated.

From the graph with NOx emissions, a much more consistent control of the boiler is observed with the ACC activated. In the first time segment, during which the boiler was controlled by the primary controls, the NOx emissions are above 200 mg/m^3 most of the time. When the ACC control was activated, the NOx emissions were reduced quite quickly to under the 200 mg/m^3 limit, and more consistent operation can be noticed. Then, again, the ACC was deactivated and NOx emissions were again increased to over the 200 mg/m^3 limit, and higher instability can be noticed. Similar conclusions can be made in the same manner further on in the chronological analysis of the NOx emissions. In the second period when the ACC was active, it can be seen that the ACC also managed well the rather big changes in biomass.

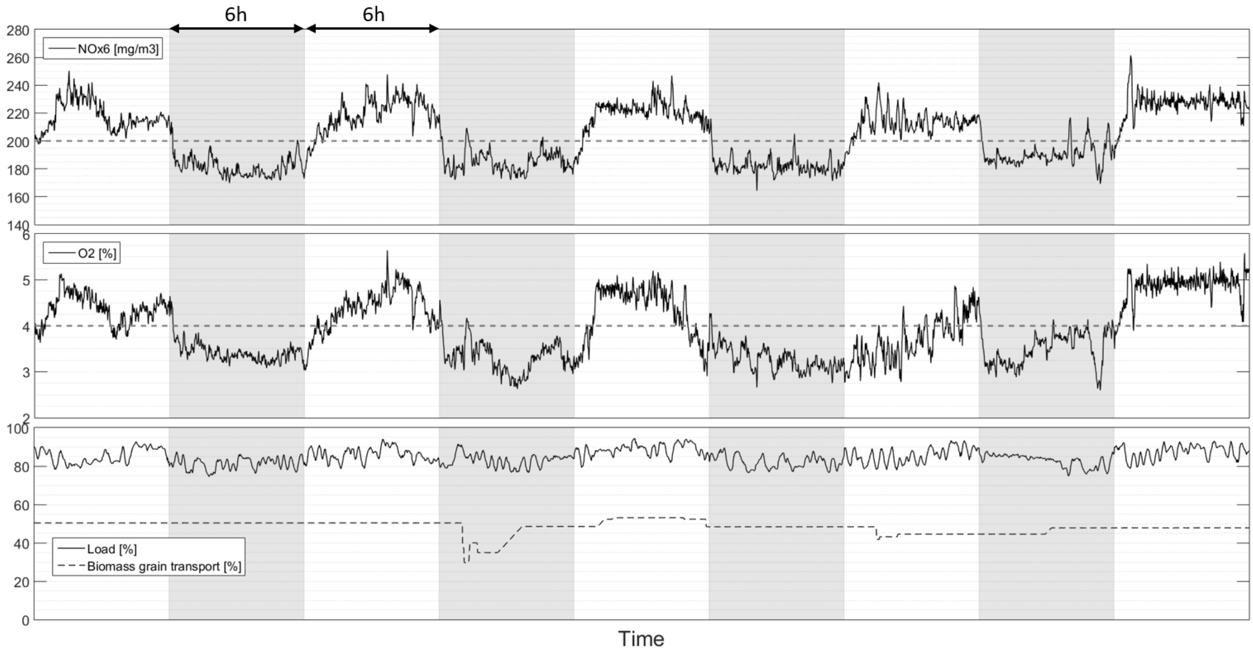

Fig. 7. Boiler control with (grey-shaded area) and without (white area) advanced combustion control.

In the test, the average NOx emissions for the time with ACC deactivated were 219 mg/m^3, whereas, with the ACC activated, they were 184 mg/m^3. As expected, the ACC control significantly improved the boiler's performance in comparison with the primary controls, hence well tackling the high dynamics of the secondary control of the power plant unit. During the test, the average loads of the boiler were 86% and 83% without and with ACC, respectively, which slightly favours the time when ACC was activated. On the other hand, when switching from ACC to primary control, the NOx emissions were still rather low for about an hour, affecting the average value. The primary controls started to slowly deviate from the optimal point, mainly due to the biomass, which represented a significant portion of the fuel in the boiler. The biomass is usually also the main cause of constantly changing characteristics and instabilities in the boiler. However, from the second test with the active ACC, there was a drop and a rise in biomass for about 20 and 8%, respectively, which was well handled by the ACC.

A significant drop in O_2 can also be observed from the second graph in Fig. 7, when comparing the test sections with and without the ACC. The average values were 3.4 and 4.3 mg/m^3 with and without the ACC, respectively, which represented a 20% decrease and thus a significant reduction in heat losses.

6. Summary

With the start of 2016, the new EU regulations on exhaust gas emissions for large power plants came into validity. The major issue represents NOx emissions, which have to be reduced from 600 mg/m^3 to 200 mg/m^3 in the years from 2016 to 2020, in the case that the operator applied for the Transitional National Plan, according to Article 32, IED Directives. This represents a big challenge for most existing power plants. In this paper, several measures that were applied to a 210 MW$_t$ coal-fired boiler co-firing biomass are presented, and the project's overall results are reported. The initial goal of the project was to reduce NOx emissions by 20 to 30% on average over the boiler's operational range. A thorough analysis of the boiler's equipment, configuration and operation was conducted, and several issues were identified. Based on these, measures related mainly to the combustion process were accepted in order to reduce NOx emissions as well as to increase the boiler's efficiency. In this regard, an 8-point-based system for measuring exhaust gases and an ESD system for measuring the distribution and velocity of pulverized coal particles were installed. The fuel delivery system and the boiler's primary control systems were upgraded and retuned. Secondary air was partly redistributed to inactive burners, and advanced combustion control solution was installed and commissioned. The results show significant improvements in the boiler's operation. The NOx emissions were reduced by 40%, exceeding the project's goal, and the boiler's efficiency was increased by 1.1%.

7. References

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