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Original Research

Biomass Co-Firing Retrofit with ROFA for NO_x Reduction

Brian Higgins[1], Li Yan[1], Hani Gadalla[1], John Meier[1], Tore Fareid[1], Guisu Liu[1], Mirosław Milewicz[2], Arkadiusz Repczyński[2], Michael Ryding[3], Włodzimierz Blasiak[3]

[1]Nalco Mobotec, 2540 Camino Diablo, Walnut Creek, CA 94597 USA
[2]Zespół Elektrociepłowni Wrocławskich, KOGENERACJA S.A., Łowiecka 24, 50-220 Wrocław, Poland
[3]Nalco Mobotec Polska, Przemyslowa 55, 43-110 Tychy, Poland

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Abstract

Nalco Mobotec's Rotating Opposed Fired Air (ROFA®) system has been installed on a RAFAKO OP-230 boiler to facilitate the co-firing of biomass by improving combustion performance and biomass burnout in the upper furnace. High velocity air is injected through multiple nozzles, resulting in strong turbulent mixing between the flue gas and fuel. The intention of this high-pressure ROFA air system is to provide better chemical interaction, increased volumetric utilization, and improved combustion. The boiler is a 50-MW corner-fired boiler burning Polish hard coal with sulfur content around 0.6% and fuel-bound-nitrogen content around 1.1%.

Prior to the ROFA installation, there was an existing SOFA system. At the same time as the ROFA installation, RAFAKO installed new low-NO_x burners (LNB) and a Nalco Mobotec consortium installed a complete biomass handling system with the capability of firing 45% of the energy input as biomass. EDF's motivation to co-fire biomass is to reduce greenhouse gas emissions. Electricity produced from renewable fuel sources is eligible for a rate increase in Poland.

The combined effect of LNB, SOFA, and ROFA results in NO_x emissions below 200 mg/Nm^3, a reduction of 43% from the LNB/SOFA operation (350 mg/Nm^3) and 63% from the pre-LNB with the SOFA-only baseline (540 mg/Nm^3). The improved combustion due to the mixing introduced by ROFA maintains loss-on-ignition (LOI) below 5%, required for continued fly-ash sales. Simultaneously, the CO emissions were held below 100 mg/Nm^3 with ROFA.

Biomass co-firing results in displacing as much as 45% of CO_2 from nonrenewable fuels. The ROFA system allows the combustion of the biomass with no noticeable increase of CO and LOI. NO_x emission is lower with biomass co-firing. Similarly, because of the lower sulfur content in biomass, co-firing results in a 36% reduction in SO_2 emissions when firing 45% biomass.

Keywords: biomass co-firing, NO_x reduction, primary methods

Introduction

In 2016, Polish NO_x emissions regulations are to drop to 200 mg/Nm^3 under the large combustion plant directive (LCPD) [1]. It is difficult to reach this level of NO_x emissions with standard OFA and SNCR systems. Due to the large number of boilers in Poland that must reach this emission level, many are installing equipment early. EdF-Wrocław Kogeneracja [2] procured the Mobotec System with three specific elements:

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*e-mail: bhiggins@nalcomobotec.com

1) Biomass transfer, milling, separation, storage and injection,
2) Rotating Opposed Fire Air (ROFA®) [3, 4] for NO_x control and combustion improvement,
3) Dedicated biomass injection ports.

There are many advantages to using biomass as a fuel for co-firing. The vegetation used for biomass energy is abundant in Poland and other European nations. Biomass is a CO_2-neutral fuel, thus co-firing biomass results in reduced greenhouse gas emissions. Biomass has a low concentration of sulfur, as compared to most fossil fuels, which reduces SO_2 emissions. Furthermore, biomass co-firing can reduce NO_x emissions. Another advantage of biomass co-firing is the increasing economic incentives for utilities to reduce greenhouse gases (such as tax incentives and Guarantee of Origin emissions trading) [5].

Biomass co-firing has many challenges. Special fuel handling is required to prevent potential combustion and explosion of the biomass as it is being transported, milled, and transferred to the biomass burners. Due to the low amount of ash in biomass fuel, small combustion inefficiencies can produce large amounts of loss on ignition (LOI), exceeding 50% [6].

EdF-Wrocław Kogeneracja mandated that biomass co-firing could not degrade plant performance. Nalco Mobotec guaranteed to maintain boiler efficiency, achieve maximum gross load, and maintain current levels of NO_x and LOI. With the addition of 45% of the heat input as biomass, ROFA was employed as a method of achieving the high levels of combustion efficiency (i.e., low LOI and CO) by introducing a highly turbulent environment in the upper furnace. The work for this project was performed by a consortium led by Nalco Mobotec and included WTS AB (www.wtsab.com) and Remak-Rozruch (www.remak-rozruch.com.pl).

Furnace Description

This OP-230 boiler operates between 25 MWe and 55 MWe. The boiler is part of a BC-50 heat generating power unit and has a back-pressure extraction turbine for district heating (type 13P55). Since the power plant was designed to provide district heating, the turbine condenser pressure is quite high (~80 kPa) and the turbine is not designed to achieve 70 MWe as would be expected for an OP-230 boiler. The boiler can reach 55 MWe and provide 179 MWt (maximum continuous output) of heating output.

The furnace side view is shown in Fig. 1. The unit is 27 m high, 7.5 m deep, and 8.4 m wide. The boiler had SOFA installed prior to the ROFA project. The existing SOFA uses from 6% to 8% of the total air flow (TAF). The existing SOFA system was kept intact during the installation of ROFA. The furnace is open below the nose with SH platens extending across the open furnace above the nose elevation.

The OP-230 boiler is a one-drum and two-pass boiler with a natural water cycle. The main boiler elements are: the drum, combustion chamber water walls, three-stage steam super heater, two attemperators, steel economizer, two rotary air heaters, and the supporting structure with a casing and platforms. The boiler is equipped with anti-explosion protection. The steam from the drum is supplied to the first stage of the convection super heater in the first pass, followed by the first steam attemperator. Then steam flows to a platen super heater (second stage), the second steam attemperator, the steam super heater of the third stage, and the outlet collector. The air is supplied to the FD fans from inside the boiler room and also from outside. A tube type economizer is located in the second pass of the boiler.

The boiler is tangentially fired with pulverized coal through burner columns in each of the four corners. The full load firing rate is 179 MWt. The boiler has newly installed LNB manufactured by RAFAKO. The plant has three coal pulverizers and each corner has six levels of coal burners.

ROFA System Design Criteria

The primary objective for installing ROFA was to enable a large-percentage co-firing of biomass. To reach this objective, the primary design criterion was to increase

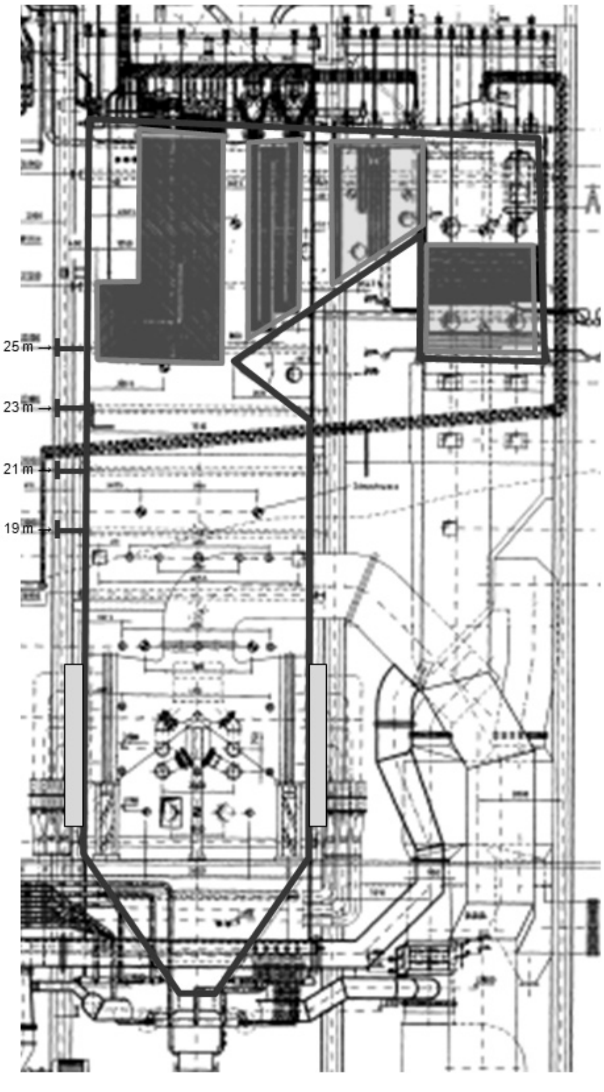

Fig. 1. Furnace side view.

mixing in the upper furnace for CO and LOI burnout. The secondary design criterion was to stage the lower furnace for NO_x reduction. A ROFA system includes a boosted-pressure ROFA fan, air duct, and air injection nozzles. The ROFA air is taken from the air preheater discharge, boosted in pressure by the ROFA fan, and delivered through nozzles into the furnace. The air pressure at the nozzles is typically 7 to 20 kPa, depending on the penetration required for mixing as determined during the CFD modeling. All flows to the ROFA nozzles are modulated based on steam flow to achieve tuned box pressures.

Biomass Co-Firing System Design

Biomass has a higher volatile content than coal, creating a potential for a combustible environment. Therefore, the handling and processing of biomass must be performed safely. To ensure plant safety and operational reliability, the biomass handling system has been designed to avoid and eliminate possible combustion within the biomass storage, transport, and milling systems. The biomass feeding system is comprised of six main components:

(1) biomass conveyance line from the fuel yard (provided by others),
(2) a pellet storage silo,
(3) hammer mills,
(4) dust separation cyclone filters,
(5) powder silo, and
(6) a biomass injection system.

The biomass fuel handling system described in this section was designed and delivered by WTS for Nalco Mobotec. Each component has been engineered to ensure safety and reliability based on WTS's experience on previous wood powder burner installations.

Biomass Process Overview

Biomass is delivered in pellet form by barge and stored in a separate fuel yard near the river. Construction of a bulk storage system is under construction but not complete. From the fuel yard, the biomass is transported to an eight-hour capacity pellet silo (Fig. 2A). Transportation to the pellet silo occurs through an enclosed, air-assisted, conveyance system. From the pellet silo the biomass is fed into the hammer mills. Large blowers draw the biomass through the hammer mills and directly into cyclone filters (Fig. 2B). Due to the large flow of air through the hammer mills (required for aspiration and transport of wood powder during milling), the mixture is potentially combustible. Spark detection, fire suppression, and air separation equipment are installed. After the biomass is milled into a powder and separated from the mill air, it is stored in a one-hour capacity powder silo (Fig. 2C). Immediately downstream of the powder silo are four feeders and four transport blowers that meter and transport the powder into the furnace through biomass burners (injecting through one of three burner elevations per corner).

Pellet Transport and Storage Silo

The biomass pellets are transported from the fuel yard by an enclosed air-assisted conveyor belt, which includes a fire-detection and suppression system. Sensors monitor the pellet feeding line temperatures. If excessively high temperatures are detected, the system stops feeding pellets into the conveyor and engages the fire suppression system. Once the combustion condition is eliminated, transport of the material is resumed. The conveyor spans 1,000 meters from the fuel yard to the pellet silo.

The pellet silo holds twelve hours of biomass when the boiler is run at full load, with 45% of the heat input coming from biomass. The storage capacity of the pellet silo was minimized to limit cost and combustion concerns, while still allowing for continued operation of the boiler on biomass when the transport of biomass from the fuel yard is interrupted. The pellet storage silo is equipped with combustion sensors, explosion panels, spark detectors, and fire suppression systems. Detectors installed near the top of the storage silo (where the biomass is fed into the silo) monitor CO concentrations. If high CO levels are detected, alarms notify plant personnel and biomass transport is halted. A fire suppression system is included at the top of the silo. Explosion panels also provide additional protection. Plant personnel are automatically notified if the explosion panels burst. If biomass combustion in the pellet storage silo continues, the silo can then be quickly evacuated by a separate screw conveyer to a location where the fire is contained with minimal impact to the biomass storage and milling equipment. The silo has high and low level indication for automatic start and stop of the pellet transport. If the level becomes too high or low, the operators are informed by alarms.

Hammer Mills

The biomass pellets exit the bottom of the pellet silo through screw feeders to two hammer mills (Fig. 3). Two

Fig. 2. Overview of Biomass Handling System: (A) Pellet Silo, (B) Cyclone Filters, and (C) Powder Silo.

Fig. 3. Picture of the hammer mill (foreground) and the motor (background) used to pulverize the biomass.

mills are included for system redundancy and to allow for mill maintenance without operational disruption. The hammer mills are equipped with a magnetic separation system and a stone trap to remove foreign particles that could cause sparks and ignition as well as damage the equipment. An air inlet at the top of the mill improves the pellet distribution through the mill to prevent uneven wearing of equipment and to facilitate optimal mill efficiency. The fans that provide the air to the hammer mill are located downstream of the mill and cyclone filters. The hammer mill can rotate in both directions, and automatically changes direction every time it is placed in operation to increase the life of the hammers and the screen. Spark and fire suppression equipment is also included at the inlet of the mill and along the transport lines to the cyclone filters. Temperature, mill amperage, and vibration are monitored to determine mill efficiency and maintenance requirements.

Cyclone Filters

A large amount of transport air is required to maintain the hammer mill temperature. When combined with pulverized biomass powder (which is volatile), the mixture creates a potentially combustible environment. Therefore, the powder is drawn through a minimal duct run (which is equipped with fire-suppression equipment) into cyclone filters (Fig. 4) to separate the biomass powder from the transport air. Each mill has a separate duct run into a separate cyclone filter for system integrity and redundancy. Differential pressure at the filter is monitored and the filter is cleaned with compressed air when required.

The fire-suppression system downstream of the hammer mill consists of multiple sensor types. A visual (spark) combustion monitor is installed in the transport line after the exit of each hammer mill. If the monitor senses a particle with high energy content, indicated by infra red radiation, or there is a number of particles with an energy content over a fixed level for a sustained time, high pressure water is sprayed downstream to quench the spark or high energy particle. The water is released at the calculated time that the spark reaches the sprayer. If IR sensors detect high energy particles, then all transport and milling operations are immediately stopped. Each cyclone filter is equipped with explosion burst panels which stop operations and notify personnel when failure has occurred.

Powder Silo and Injection System

Pulverized biomass, after the cyclone filters, is collected in the powder silo. The capacity of the silo is sufficient for about thirty minutes at 45% heat input from biomass at full load operation. The small capacity avoids prolonged storage of unused material. The silo is equipped with explosion panels and sensors indicating if failure has occurred.

Four separate lines are fed by volumetric metering feeders and transported to the biomass injection ports via four separate Roots blowers. A bridge breaker is located at the bottom of the silo to break-up any material that might bridge across the silo, as well as to provide even material distribution to the four feeders. The bridge breaker is controlled by inductive sensors located above the feeders. If the inductive load changes, indicating a lack of biomass, the bridge breaker is engaged to get the biomass moving again. Three load cells are installed on the powder silo to determine the mass flow rate of the biomass and to verify the feeder calibration.

Transport air controlled to maintain a constant velocity at all loads. Each feeder line is equipped with a three-way

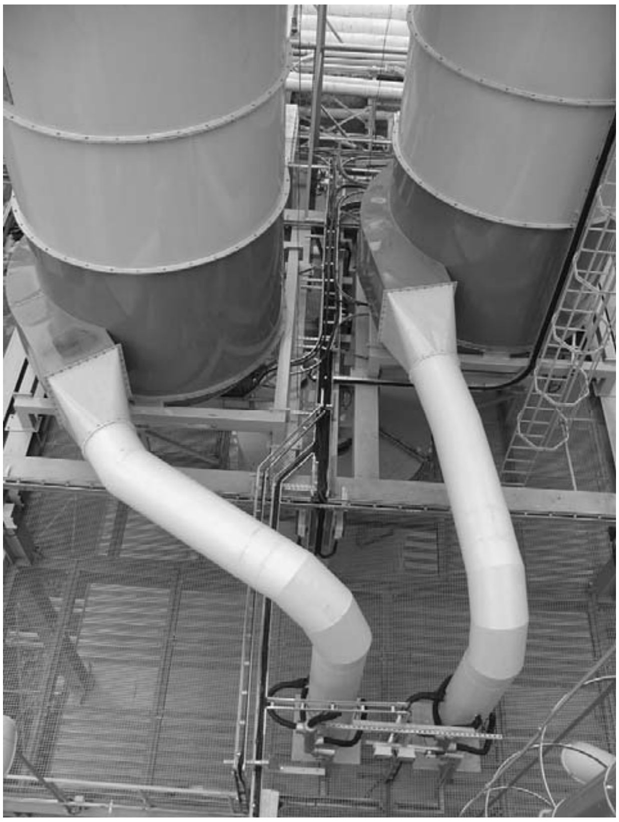

Fig. 4. Picture of the dual cyclone filter system.

splitter with three knife-gate valves immediately upstream of the furnace to direct the biomass to one of three injection locations. The biomass injection location is varied according to which coal mill is in operation and was varied as a tuning parameter.

CFD Modeling

Combustion Model Overview

Nalco Mobotec utilizes FLUENT for CFD modeling simulations, simultaneously solving for density, velocity, temperature, and chemical species (including fuel volatiles) concentration fields of the gas phase and fuel particle properties and combustion within the furnace to steady state. The gas phase conservation equations are solved using a variable density, quasi-incompressible formulation embedded in a Eulerian reference frame, while the fuel particles are solved using a Lagrangian reference frame. The governing equations are gas phase continuity, momentum, turbulent kinetic energy, turbulent dissipation, enthalpy, and the species conservation equations for each gas species in the turbulent combustion model. These conservation laws have been described and formulated extensively in standard CFD textbooks. A k-ε turbulence model was implemented in the simulations. The standard Eddy-Breakup (EBU) turbulence combustion model is used. The following two step mechanism was utilized for fuel combustion:

$$\text{Fuel} + a\, O_2 \rightarrow b\, CO + c\, CO_2 + d\, H_2O + e\, SO_2 \qquad (1)$$

$$CO + 0.5O_2 \rightarrow CO_2 \qquad (2)$$

...where the stoichiometric coefficients (a, b, c, d, and e) are determined from the fuel proximate and ultimate analyses.

Fuel is introduced in the simulation through burner geometry by specifying a Rosin-Rammler particle size distribution and a calculated particle velocity slightly less than the gas phase velocity within the primary air injectors. Parameters for fuel distribution are derived from sieve measurements of fuel samples collected onsite. This applies to both coal and biomass injection. Gas phase air flow rates are specified at the primary, secondary, and ROFA ports using appropriate inlet angles, temperatures, and turbulence intensities.

The CFD model uses different expressions for particle heating and reaction at each stage of the process. An inert heating law applies when particle temperature is less than the onset temperature for devolatilization. Particle heating is caused by convective heat transfer from the gas phase and the radiant flux from the furnace. During devolatilization and char oxidation, the particle energy balance also includes a heat of devolatilization and heat of combustion, in addition to the convective and radiative heat transfer rates. Both diffusion and intrinsic kinetics were included in the char oxidation sub-model.

FLUENT NO_x submodel involves sophisticated fuel-N conversion pathways. After fuel devolatilization, fuel-N is partitioned into volatiles-N and char-N. HCN is the dominant nitrogen species in volatile-N released from coal, and NH_3 is the dominant nitrogen species released during biomass devolatilization. Char-N is released into the gas phase at a rate that is proportional to the carbon burnout rate. Because char-N conversion chemistry is complex, the simulation assumes a fixed fraction of char-N directly converted to NO with the rest of N converted to N_2. This assumption is often used in literature [7]. The gas phase NO can be reduced to N_2 by CO, on the char surface, or through ammonia/urea injection.

Biomass combustion has been previously modeled by Nalco Mobotec; including 100% biomass on grate-fired boilers, biomass co-firing with coal in tangentially-fired boilers, and 100% biomass in wall-fired boilers. Biomass combustion is modeled using the DPM modeling approach provided by FLUENT, similar to pulverized coal combustion modeling; however, several specific features are required for biomass combustion:

Large Particle Size and Non-Spherical Shape

Biomass particles, after milling, are much larger than pulverized coal. Also, the shape of the biomass particles is affected by the fiber content such that the aspect ratio (length/width ratio) is much higher than for pulverized coal. These physical characteristics lead to enhanced drag forces imposed on biomass particles [8], and also to an enhanced diffusion mass transfer of O_2 onto the particle surface from the bulk gas [9]. For biomass modeling for this project, a non-spherical shape is assumed with a shape factor less than one.

Devolatilization

During devolatilization, the swelling effect of the particles is also taken into account because of the significant fraction of volatile matter in the fuel. Compared to pulverized coal combustion, biomass devolatilization has been shown to proceed much faster under similar environmental conditions. The on-set temperature of devolatilization is normally lower than for pulverized coal combustion. Experimental data for biomass devolatilization kinetics were used in a single-rate kinetic model for devolatilization, where the pre-exponential factor was much higher than that for pulverized coal [10].

Char Chemistry

It is commonly acknowledged that biomass char surface combustion is much faster than for pulverized coal due to enhanced mass transfer (physical shape) and intrinsic reaction kinetics (carbon micro-structure). In our modeling approach, diffusion and kinetic control models were used. A diffusion rate constant is used to account for the enhanced mass transfer. For the kinetic surface reaction, a pre-exponential factor and the activation energy term were selected from the literature [10], and result in much faster kinetics than for coal.

Geometry and Model Inputs

As shown in Fig. 5, the furnace enclosure for the CFD model domain for baseline, ROFA, and biomass co-firing cases is defined as beginning at the burners and ROFA ports (inlet boundary conditions) and ending at the vertical plane downstream of the primary super heater and reheater in the backpass (outlet boundary condition). The furnace volume extends upstream to the bottom ash hopper. The super heat pendants are depicted in the model using the actual number of tube bundles and dimensions to account for heat absorption and flow stratification. The furnace geometry was represented in the computer model with approximately 1,400,000 computational cells in an unstructured, hybrid (all hexahedral) grid. The large number of computational cells is sufficient to resolve the most relevant features of the three-dimensional combustion process.

The burner layout and dimensions were taken from drawings provided by the plant. For the coal, there are three mills. Each provides coal to two burners in each corner (8 burners per mill). There are six coal burner elevations and three biomass injector elevations. Each of the four biomass feeders feeds one of three biomass burners in each corner (for a total of 12 biomass burners). Only one burner in each corner is used at a time (for a total of 4 biomass burners in use). The specific biomass burner that is in use is matched to the specific coal burner set that is in service. Typically, when biomass is co-fired, only one coal mill is in service. The biomass burners are physically located upstream (~1 m) of the coal burners.

Table 1. Baseline System Operating Conditions.

		Coal Only	Co-firing
Firing Rate	[MWt]	179	179
Fuel	[heat input %]	100% coal	55% coal + 45% biomass
Excess Air	[%]	20	20
Excess O_2	[% dry]	3.6	3.6
Coal Flow	[t/h]	23	13
Biomass Flow	[t/h]	0	15
Total Air Flow	[t/h]	254	245

Key inputs for the furnace CFD baseline simulations are listed in Table 1. The modeled coal and biomass composition were provided by the plant and are listed in Table 2. The firing rate was calculated by the coal flow and coal heating value. The total air flow (TAF) was calculated from the reported coal composition and measured economizer O_2 concentration. The particle size distribution measurements and assumed Rosin-Rammler distribution are plotted in Fig. 6. The non-spherical shape of the biomass was taken into account by using a non-spherical shape factor of 0.6 in calculating the drag force.

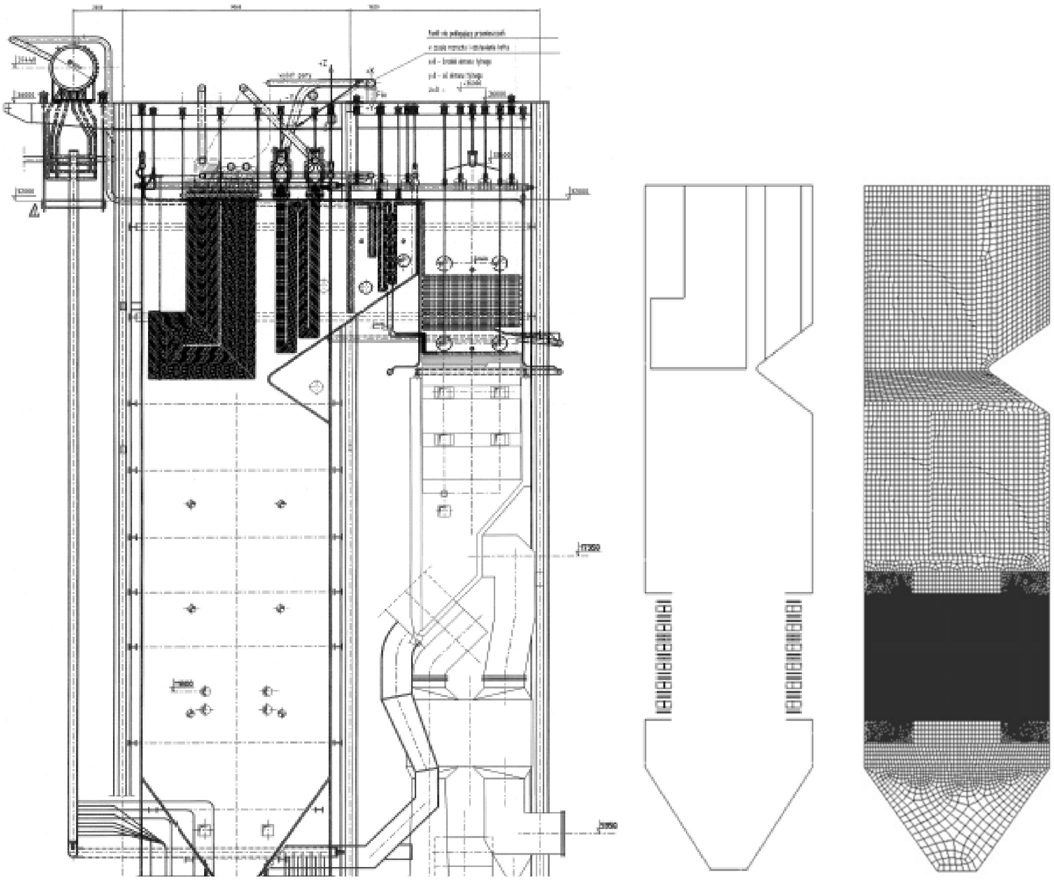

Fig. 5. Side sectional drawing (left), CFD domain (middle), and CFD mesh (right).

Table 2. Fuel Analysis.

Proximate Analysis		Coal	Biomass
Moisture	[wt.% ar]	9.20	8.80
Ash	[wt.% ar]	9.05	2.4
Fixed Carbon	[wt.% ar]	52.55	15.3
Volatile	[wt.% ar]	29.20	73.5
HHV	[kJ/kg ar]	27,712	18,969
Ultimate Analysis			
Carbon	[wt.% ar]	67.37	47.0
Hydrogen	[wt.% ar]	4.37	5.0
Oxygen	[wt.% ar]	7.99	36.23
Nitrogen	[wt.% ar]	1.11	0.49
Sulfur	[wt.% ar]	0.60	0.08

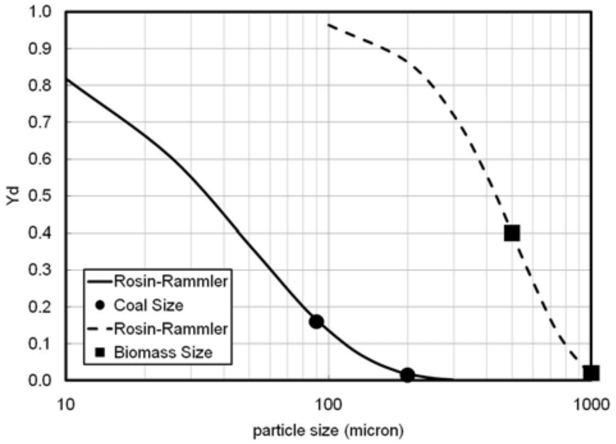

Fig. 6. Coal and biomass particle size distribution. Yd is the mass fraction in excess of the indicated particle size.

CFD Modeling Results

In this section the results of baseline model are first discussed, followed by a discussion of the ROFA results. The contours of calculated field variables (i.e. temperature, O_2, CO, NO_x, and turbulent kinetic energy) for the baseline with LNB, and coal-only ROFA case, and biomass ROFA case are compared. Baseline refers to the case with the RAFAKO LNBs, firing coal only.

Temperature Distribution

The temperature distribution of several horizontal planes at different elevations in the baseline case appears in the left panel of Fig. 7. This figure shows that the majority of the coal combustion occurs in the burner zone below the nose. The maximum flame temperature in the baseline furnace is about 1,500ºC. The temperature distribution also indicates that coal ignites soon after being injected into the furnace. The flame then propagates and expands as flow continues into the center of the furnace. This rapid ignition is due to the release of volatiles of the coal during rapid heating. As is typical in a tangential-fired unit, a rotating fire ball is formed in the furnace center. Interestingly, the center of the fire ball is cooler since initially the combustion zone surrounds the center of the fireball. As the flue gas proceeds to the upper furnace, the fireball burns through and gradually cools as the heat is absorbed by the water walls.

The temperature distribution of coal-only ROFA case appears in the middle panel of Fig. 7. No significant change of the burner zone temperature distribution is observed between baseline and ROFA case. ROFA jet penetration into the upper furnace is, however, seen in the temperature distribution. The baseline upper furnace temperature around nose region is hotter than ROFA case, but in the radiant super heater region, the ROFA case showed better temperature distribution.

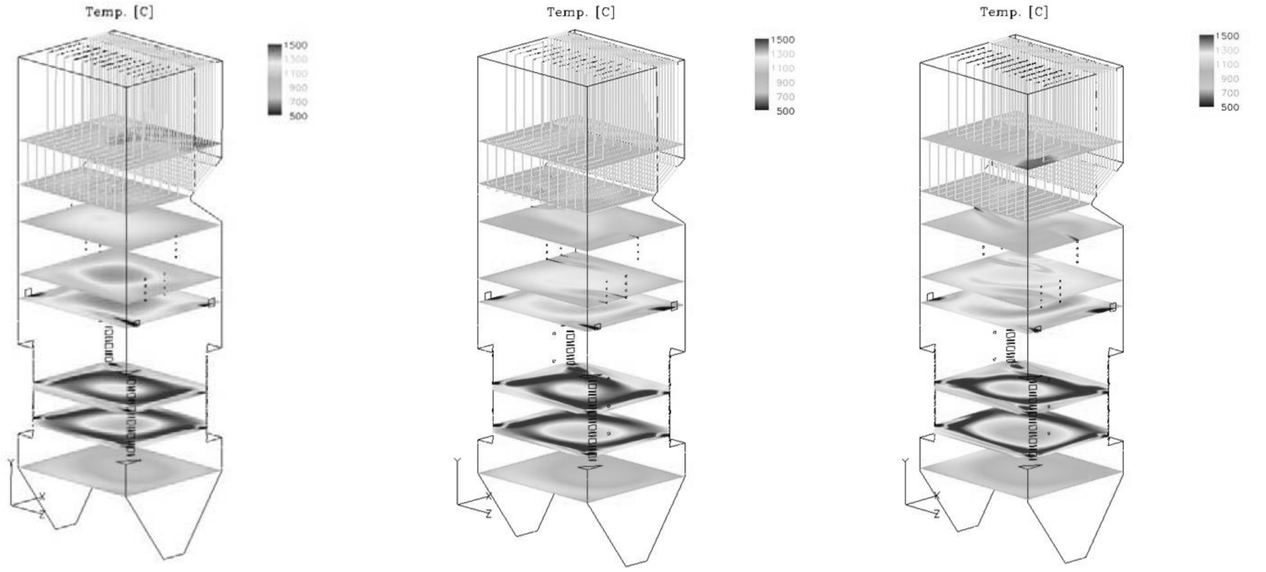

Fig. 7. Gas temperature of (left) baseline with LNB, (middle) coal-only ROFA and (right) biomass ROFA.

The temperature distribution of the Biomass ROFA case in the right panel of Fig. 7 shows more concentrated combustion as opposed to the coal case. This is because of the volatiles from biomass being released and burned faster. In the upper furnace, the temperature distributions between coal-only ROFA and biomass ROFA cases are similar, except for a cool region in the front-left corner of the co-firing case. Fine tuning of ROFA in the field is able to improve the temperature distribution and eliminate the cool spot in the corner.

Because of better mixing with ROFA, the temperature distribution for the biomass ROFA case is significantly better than for the baseline case. This is essential to co-fire high levels of biomass.

O_2 Distribution

Fig. 8 shows the O_2 distribution of three cases. A low O_2 fire ball is seen in the furnace center in baseline case, and this low O_2 region persists as flue gas travels to the upper furnace. In the burner zone, a relatively high O_2 region is seen attaching to the water wall, which will help eliminate the possibility of slagging and corrosion. In the middle panel of Fig. 8 for the coal-only ROFA case, the average O_2 in burner zone is lower than the baseline case. A low O_2 (consequently high CO) pocket is observed in the upper furnace. Fine tuning of ROFA is able to eliminate this pocket. In the right panel for the biomass ROFA case, the low O_2 high CO pocket is much smaller.

NO_x Distribution

Fig. 9 shows the NO_x concentration distribution for the three cases. The baseline NO_x kinetic parameters were adjusted to match the reported baseline NO_x of 540 mg/Nm^3. Once the baseline parameters were set, they were not changed in the NO_x prediction for other cases. In the left panel of Fig. 8, NO_x was predominantly formed in the burner zone and upper furnace zone where coal is burned with excess O_2. As observed in the middle panel of Fig. 8, due to air staging in burner zone by ROFA, NO_x is reduced in the

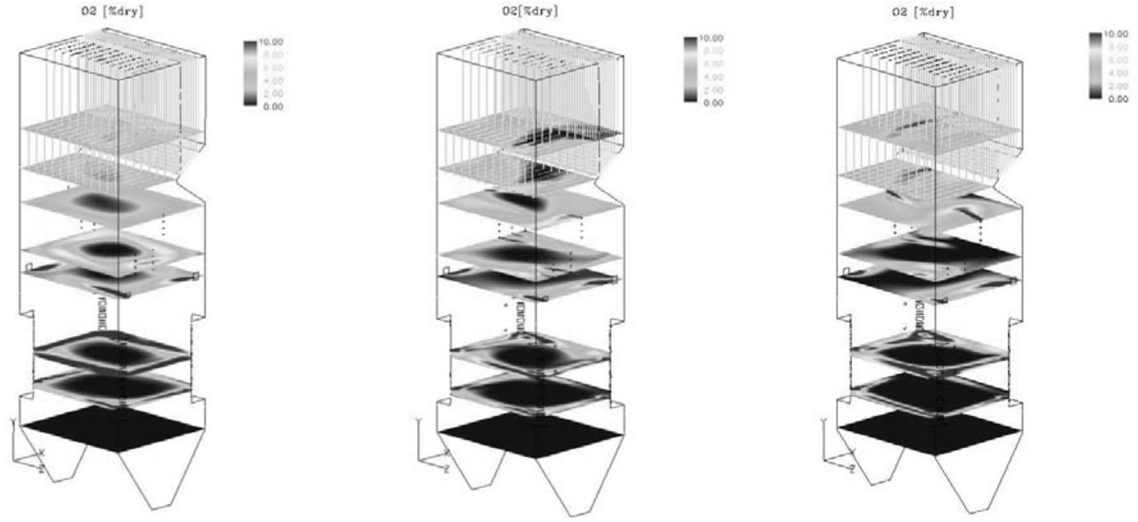

Fig. 8. Oxygen contours of (left) baseline with LNB, (middle) coal-only ROFA and (right) biomass ROFA.

Fig. 9. NO_x contours of (left) baseline with LNB, (middle) coal-only ROFA and (right) biomass ROFA.

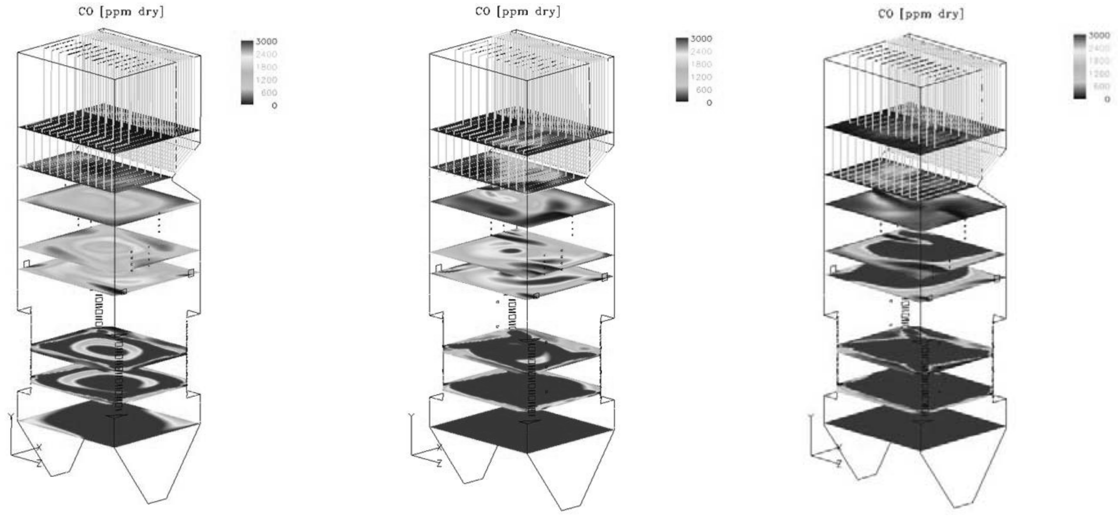

Fig. 10. CO contours of (left) baseline with LNB, (middle) coal-only ROFA and (right) biomass ROFA.

ROFA case. Under reducing atmosphere, the dominant NO_x reduction mechanism is that HCN released in volatiles as the dominant nitrogen species reacts with NO_x to form N_2.

Biomass co-firing further reduces NO_x significantly as observed in the right panel of Fig. 9. The predicted NO_x reduction is due to the following reasons: first, the biomass nitrogen content is less than half of the coal; second, in the biomass co-firing case, most of fuel nitrogen is released as NH_3 in volatiles, which becomes a NO_x-reducing agent in the reducing environment.

CO Distribution

Fig. 10 shows the CO distribution of three cases. In all cases, tens of thousands of ppm of CO are formed in the burner zone. Due to staging, more CO is formed in ROFA cases than the baseline case. However, ROFA is designed to burn CO faster than baseline, as demonstrated in Fig. 10. In the coal-only ROFA case, there is a low O_2 pocket in the upper furnace. Consequently, this low O_2 pocket is responsible for high O_2 as seen in the middle panel of Fig. 10. Again, during tuning of ROFA, air is directed to eliminate the CO pocket.

Turbulent Kinetic Energy

The mass weighted turbulent kinetic energy of all cases is plotted in Fig. 11. In baseline, the maximum turbulent kinetic energy appears in the near burner zone at the lower furnace because of the high velocity of the burner air injection. However, this highest turbulent rapidly diminishes as these jets penetrate into and mix in the furnace. In ROFA cases, a significant area with a magnitude higher turbulent kinetic energy appears at the ROFA injection zone in the upper furnace, due to high injection velocity of ROFA air.

Turbulence is dissipated into the bulk flow through eddy dissipation. That is, a large amount of kinetic energy results in better mixing between the ROFA air and the products of incomplete combustion. High turbulent mixing promotes the chemical reaction, which is the reason for rapid burnout of CO in ROFA cases.

One fact not discussed above is that the coal-only ROFA case was modeled early in the design phase and the biomass ROFA case was modeled late in the design phase. As such, the biomass ROFA case includes several design iterations, producing better predictions. Several points are apparent: first, the design iteration is able to achieve a better distribution of O_2 and reduce CO throughout the upper furnace; second, more air in the later design was distributed into the upper furnace. This second point is clear in Fig. 11 from looking at the kinetic energy distribution in the upper furnace. This illustrates the point that the CFD model is used for design. We also use our field experience and include sufficient design margin to allow for ample onsite tuning after installation.

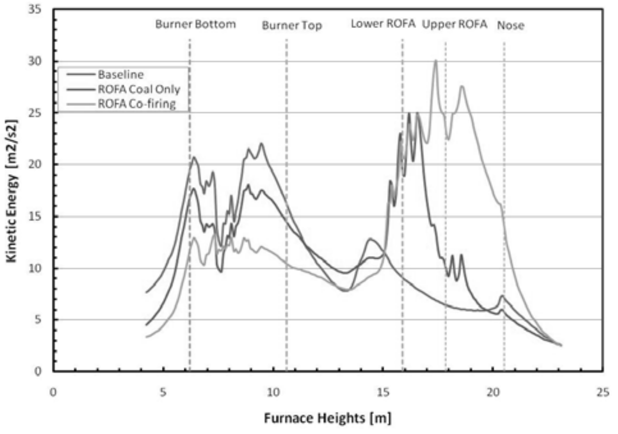

Fig. 11. Mass-weighted kinetic energy of baseline with LNB, coal-only ROFA and co-firing with ROFA.

Field Performance

Low-NO_x Burner Operation

Before the LNB system was installed, the original SOFA produced 540 mg/Nm^3 of NO_x (reported by the plant). NO_x was measured at the stack. The boiler has an online LOI monitor that is routinely calibrated with ash sampling. The boiler is operated to keep LOI below 5% to allow the owner to sell their ash instead of landfilling it. The SOFA system has historically run with 6% to 8% of the total air flow. This is insufficient staging to create a sub-stoichiometric burner zone and is likely the reason for the high (540 mg/Nm^3) NO_x emissions with SOFA.

During the outage, RAFAKO installed on LNB system and the NO_x emissions dropped to around 350 mg/Nm^3 before the start of ROFA tuning. In Fig. 12, the NO_x emissions and LOI measurements are plotted versus unit load. NO_x emissions vary from 250 to 450 mg/Nm^3, and average about 350 mg/Nm^3. In the figure, the trend line is sketched and is not calculated. The LOI measurements are on average around 5%. The LNB system works by controlling the fuel-and-air distribution in the fireball, creating a central reducing environment zone for NO_x reduction.

In Fig. 13, the same NO_x and LOI data are plotted versus the burner stoichiometric ratio (BSR). Even with the SOFA in service, the BSR is well above 1.0, indicating that the burner zone is not overall staged and the center of the fireball is likely to be slightly staged. The variability in the BSR in Fig. 13 is due to changes in the excess air and load. As the excess air is lowered, the center of the fireball is staged slightly more, which produces less NO_x. This effect is shown by plotting NO_x versus BSR.

Also shown in Fig. 13 is the effect on staging on LOI. As the fireball is starved of oxygen, NO_x goes down, but LOI goes up. This is a common limitation of primary NO_x reduction methods; namely a tradeoff between NO_x reduction and complete combustion (CO and LOI). Although a further reduction in excess air, or high SOFA flow rates, would decrease NO_x further, the amount of possible NO_x reduction is limited by the formation of LOI.

ROFA Operation – Coal Only

With ROFA installed, a significant fraction of the total air flow is redirected from the burner zone and introduced downstream of the SOFA ports. This redirected air is injected through the ROFA ports at high velocity, which promotes fuel and air mixing for more complete combustion (i.e., lower LOI and CO).

Fig. 14 shows the NO_x and LOI levels with ROFA in operation (red symbols) alongside the baseline data from Fig. 13 (blue symbols). Since this data was acquired during the tuning phase, the trend lines are added to represent the expected final tuned conditions. NO_x reduction with ROFA is clear. NO_x is under 200 mg/Nm^3 for most of the load range, and reaches 170 mg/Nm^3 for low load. LOI is again variable, but averages around 5% (similar to the baseline case).

Fig. 15 shows NO_x and LOI as a function of the BSR. As BSR is reduced, a larger portion of the fireball becomes sub-stoichiometric and large NO_x reductions are observed. There is a clear trend between BSR and NO_x. The observed variation in this trend is due to (1) tuning and (2) load.

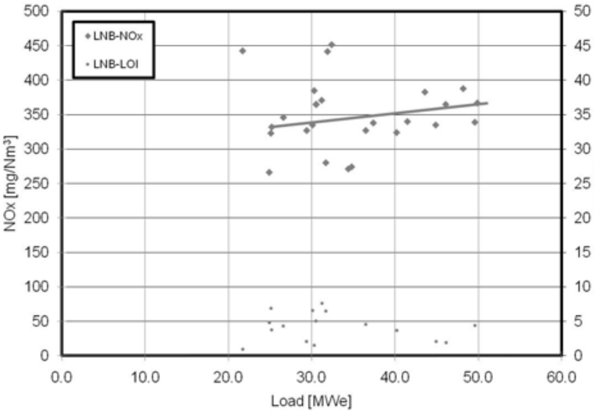

Fig. 12. LNB (no ROFA) NO_x and LOI as a function of load [MWe].

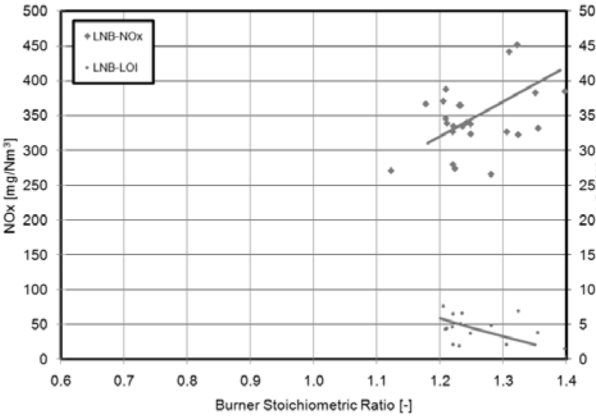

Fig. 13. LNB (no ROFA) NO_x and LOI as a function of the burner stoichiometric ratio (BSR).

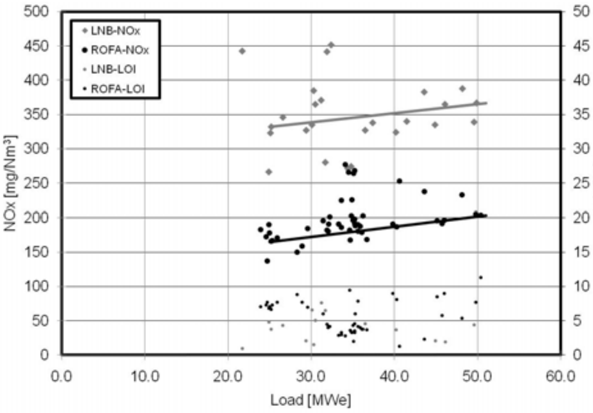

Fig. 14. LNB only and LNB/ROFA NO_x and LOI as a function of load.

Also, as seen in the baseline case, there is a tradeoff between further NO_x reduction and LOI. As the boiler is staged deeper, LOI increases. Low NO_x emission comes at a penalty of LOI.

For a burner stoichiometric ratio between 0.87 and 0.92, while firing 100% coal, NO_x can be maintained below 200 mg/Nm^3 with overage flyash LOI kept below 5%. Without ROFA, maintaining LOI at 5% requires a BSR of 1.2, resulting in NO_x emissions of 350 mg/Nm^3.

ROFA creates large-scale turbulence and fuel-air mixing in the upper furnace. This allows oxygen to reach CO and LOI, resulting in higher rates of reaction and lower CO and LOI.

In Fig. 16, CO emissions (instead of LOI) are plotted versus BSR for the ROFA case and the ROFA-off case. The trends in CO are similar to LOI in Fig. 15. This illustrates the importance of ROFA on upper furnace mixing. In the upper furnace, the temperature is sufficiently hot for fast CO oxidation, and CO emissions are due to poor mixing between CO and oxygen in the open furnace.

For the coal-only case, the combined effect of ROFA on NO_x reduction is to reduce the LNB NO_x from 350 mg/Nm^3 to below 200 mg/Nm^3, a reduction of 43%. There is a 63% reduction in NO_x from the historical NO_x levels of 540 mg/Nm^3. Improved combustion due to the mixing introduced by ROFA maintains LOI below 5%, required for flyash sellability. This level of LOI cannot be reached by burners alone unless burner stoichiometry is held above 1.2. Concurrent with NO_x emissions below 200 mg/Nm^3, ROFA can maintain CO emissions below 100 mg/Nm^3.

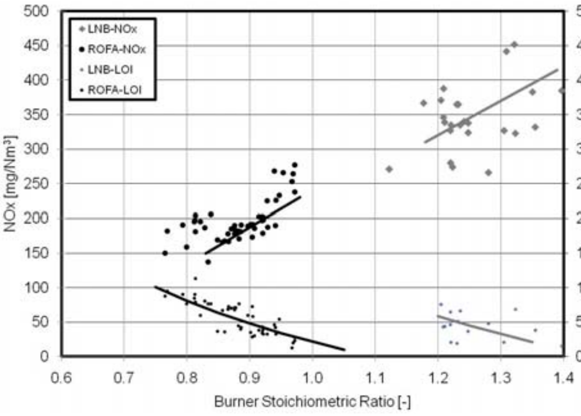

Fig. 15. LNB and LNB/ROFA NO_x and LOI as a function of the burner stoichiometric ratio (BSR).

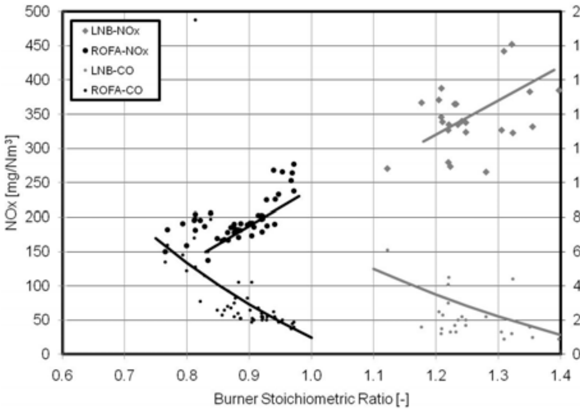

Fig. 16. NO_x and CO as a function of the burner stoichiometric ratio (BSR) for LNB only and with ROFA.

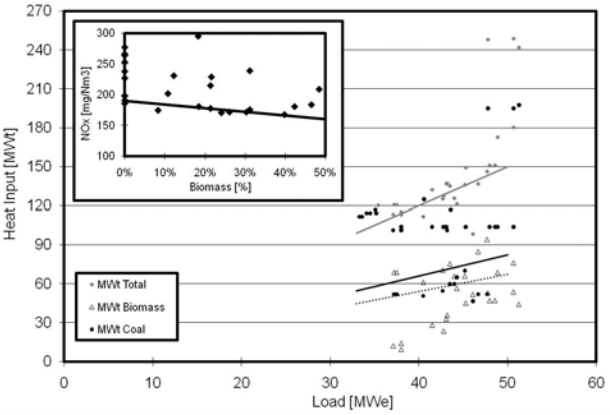

Fig. 17. Total heat input is plotted versus load, showing the proportion provided by biomass and coal. The inset figure shows the decrease in NO_x as more biomass is fired.

ROFA Operation – Biomass Co-Firing

This boiler has been retrofitted to co-fire biomass with coal. The method for co-firing biomass is to start and operate the boiler while firing coal, and then introduce biomass to increase (and control) load. Each of the three coal mills typically provides a heat input of about 64 MWt at minimum mill operation, which generates 16 MWe. The minimum heat input from the biomass feeders is 9 MWt, which generates 3 MWe. A typical operating mode would be to start the boiler up on one mill to 16 MWe and then start feeding biomass, initially reaching 19 MWe (15% heat input with biomass). Then the biomass is increased until a load of 29 MWe is reached (45% heat input with biomass). From 29 MWe to full load, both coal and biomass are increased together, keeping the coal/biomass heat input ratio constant. By co-firing 45% of the heat input with biomass (without a significant heat rate penalty due to the biomass), the greenhouse gas emissions are reduced by 45%.

Fig. 17 illustrates a number of operating conditions (showing actual running data), where the total heat input, biomass heat input, and coal heat input are all plotted versus the load generated. In the Fig. 17 inset, NO_x is shown to be reduced as the percent biomass is increased.

Fig. 18 shows that NO_x when co-firing biomass is lower than coal-only. This is consistent across the load range. This result is expected as the nitrogen content of the biomass is lower than the coal and the volatility is larger. Lower nitrogen and higher volatility are helpful for NO_x reduction in a deeply staged furnace since the volatile fuel-bound nitrogen becomes a reducing agent for the thermal NO_x produced at the hottest portion of the flame zone.

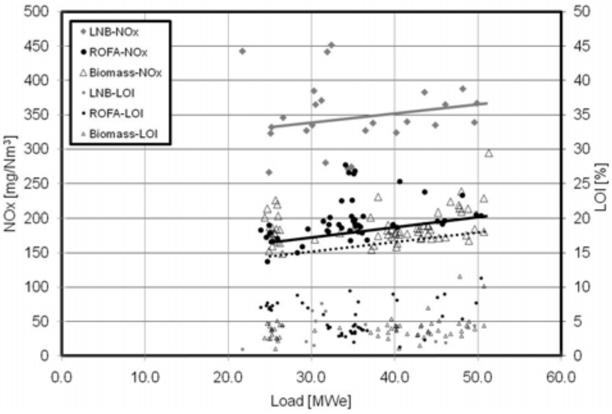

Fig. 18. NO_x and LOI as a function load [MWe] with and without biomass co-firing.

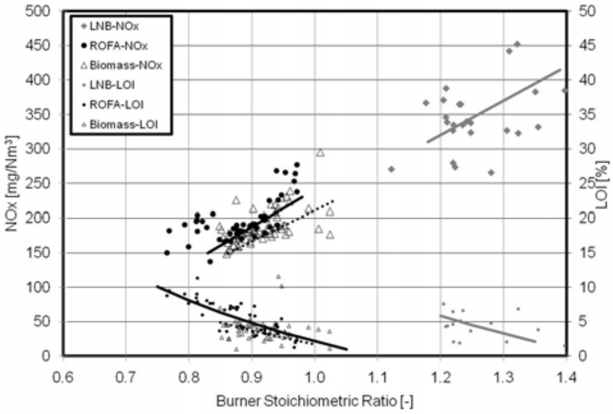

Fig. 19. LNB and LNB/ROFA NO_x and LOI as a function of the burner stoichiometric ratio (BSR) with and without biomass co-firing.

Fig. 19, which shows NO_x and LOI as a function of BSR, confirms that the NO_x emission is lower with biomass co-firing. It also shows that the LOI is lower when co-firing biomass. This is surprising because the biomass has a low ash fraction and small amounts of unburned carbon, resulting in high LOI values. For example, a coal with 9.1% ash (Table 2) will only have 5% LOI if there is 0.7% unburned carbon. But for biomass with 2.4% ash, the same unburned carbon will result in 13% LOI.

Because of the different ash content of the two fuels, co-firing boiler at 45% heat input of biomass reduces the ash input of the boiler by 27.6%. Assuming that the LOI from the coal is unchanged, the unburned carbon from the biomass ash must be less than 0.26% unburned carbon to maintain the 5% LOI in the flyash.

The fact that the LOI has actually decreased indicates that the high ROFA velocity introduces sufficient mixing to burn the fuel (especially the biomass) to maintain the low levels of LOI. While combustion in the upper furnace is improved by ROFA, the highly volatile biomass burns in the lower furnace at higher temperature and may help increase the devolatilization rate of the coal, reducing the LOI from the coal as well.

Because the sulfur content in biomass is much lower than coal, biomass co-firing has the added advantage of SO_2 reduction. At 45% biomass firing rate, the SO_2 emission is reduced by 36%.

Alternative Biomass Testing

Nalco Mobotec and EdF-Wrocław Kogeneracja tested several different biomass fuels. The work presented above was solely for dry wood-sourced biomass pellets. The alternative biomass fuels considered were:

1) Straw pellets
2) Willow pellets
3) Wood pellets

Fig. 20 shows the results of the biomass co-firing tests, with NO_x emissions and LOI in the flyash as a function of BSR (superimposed on the data presented previously). The NO_x emissions for the varying biomass fuels are consistent with the original biomass (wood) co-firing, showing a slight decrease in NO_x relative to coal-only combustion. LOI is less consistent, showing more fluctuations due to variable moisture content as a result of weather conditions. Because of the decrease in NO_x, it is expected that a small increase in burner stoichiometry would result in maintaining the LOI below 5% while allowing for NO_x near or below 200 mg/Nm³. The results show that the Nalco Mobotec biomass installation at EdF-Wrocław Kogeneracja has flexibility in handling and co-firing different biomass fuels.

Conclusions

Because of governmental mandates and incentives, many power plants in Poland are considering biomass co-firing. EdF-Wrocław Kogeneracja has converted Unit 1 to co-fire biomass up to 45% of the heat input. As part of the biomass conversion, Nalco Mobotec achieved the following:

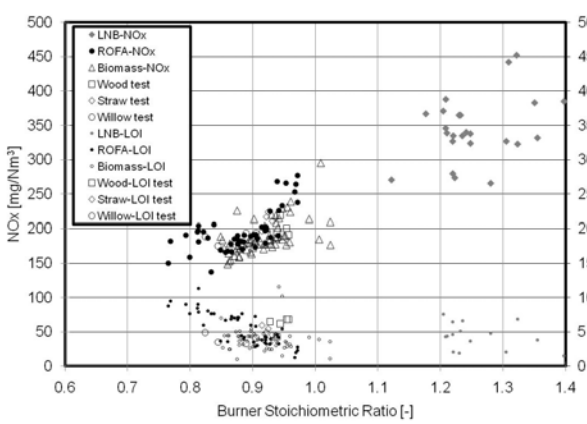

Fig. 20. NO_x and LOI as a function of BSR for varying biomass fuel tests.

1) ROFA enables efficient combustion of a large percentage of biomass co-firing (above 30% up to 100%), including agro-biomass with high fuel nitrogen content).
2) ROFA simultaneously provides high NO_x reduction with very low LOI for both coal and biomass co-firing conditions.
3) ROFA allows the boiler to operate at full load while co-firing a large percentage of biomass without harming steam production and steam quality.
4) ROFA reduced NO_x to below the 2016 emissions levels of 200 mg/Nm^3 from a baseline value of 540 mg/Nm^3 with LOI below 5%.

The project included:

(1) installation of RAFAKO LNB coal burners,
(2) installation of biomass fuel handling, pulverizing, and injection into the boiler, and
(3) design and installation of ROFA ports and biomass burners and locations.

Because of the safety concerns of biomass handling, Nalco Mobotec installed many safety features and system redundancies to minimize the potential for biomass combustion or explosion in the transport and handling process. Four feeders are installed to deliver biomass fuel to each corner of the boiler. Extensive CFD modeling was used to design the ROFA system and to locate the proper elevation for the biomass burners.

The low-NO_x burners reduced the NO_x emissions of the boiler from 540 mg/Nm^3 to 350 mg/Nm^3. Without ROFA operations, the LOI and CO emissions are sensitive to burner stoichiometry. The ROFA system stages the combustion in the lower furnace for reduced NO_x levels and increases the mixing in the upper furnace, thereby increasing the extent of the combustion. Furthermore, ROFA's unique design introduces internal recirculation of the flue gas and fuel particles in the boiler, allowing for better utilization of the furnace volume for combustion and heat transfer. With ROFA in-service, a BSR less than 0.92 results in NO_x emissions below 200 mg/Nm^3, the 2016 emission target in Poland. CO levels and LOI percentage increase beyond their desired levels for BSR less than 0.87. Therefore, the boiler has a comfortable window of operation where NO_x emissions are met without exceeding an LOI of 5% (necessary of flyash sellability) and without exceeding 100 mg/Nm^3 of CO.

The installation allows for 45% of the heat input to be biomass without reducing the efficiency of the boiler. Therefore, CO_2 from nonrenewable fuels is reduced by 45%. Biomass co-firing results in a further reduction of NO_x due to the reduced amount of fuel nitrogen in biomass. Because sulfur in the biomass is only 3% that of coal (on a heating value basis), 45% biomass co-firing reduces SO_2 emissions by 36%. The ROFA system allows for biomass co-firing with CO and LOI levels similar to that of coal-only combustion. Nalco Mobotec tested different types of biomass fuels, including wood, straw, and willow pellets. The NO_x levels are consistent among the different biomass fuels. With the different biomass fuels, NO_x emissions below 200 mg/Nm^3 while maintaining the acceptable levels of CO and LOI are possible, but some ROFA system tuning for significantly different biomass fuels is required to achieve good results.

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