

FUEL SWITCH FROM FOSSIL TO 100 % BIOMASS ON TANGENTIAL FIRED PC BOILER

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INTRODUCTION

Combustion process optimization, emission reduction for maximum availability, and reliability of utility boilers operation independently on available fuels including biomass are important factors influencing power plant management and operational costs. These can be influenced substantially by implementation of emission reduction techniques required by Large Combustion Plant Directive (LCPD), [1]. One of main issues is NO_x and CO₂ reduction for a wide range of available fuels and boiler loads. Due to lower investment costs in comparison to “end of tube” techniques, NO_x emission reduction by means of in-furnace methods is commonly used. These methods are based on combustion process modification. At present there are many commercially available combustion modification methods used to optimize combustion and limit formation of pollutants. Combustion modification is usually followed by in-furnace reduction methods. Although there are many ways to modify a combustion process, there are only a few which modify the combustion process and can still guarantee minimum emissions, complete combustion, maximum boiler efficiency, and low operational and maintenance costs.

Some power plants must often use different coals, biomass or even waste fuel. Thus, modern combustion processes must be fuel flexible and must be able to accommodate changing fuel supplies. It has to also be able to utilize difficult fuels and reduce negative effects of fuel blends by enabling direct co-firing; for example, coal and biomass.

VOLUMETRIC COMBUSTION SYSTEM

Traditional air staging systems are not uncommon in utility and district heating boilers independent of firing configuration or combustion technology. However, NO_x reduction for traditional systems is limited.

Typical organization of staged combustion is shown in Figure 1. In order to prevent formation of nitrogen oxides from fuel-bound nitrogen, the primary combustion zone is operated under sub-stoichiometric conditions with excess air number (λ) less than one. To complete combustion a secondary air is introduced into the upper furnace by means of air supply system called Over-Fire Air (OFA). The secondary combustion zone is operated with excess air number (λ) above one. Interaction between the two separated combustion zones is difficult to control in large scale combustion chambers particularly when boiler's load and operational parameters change. Negative effects of such staged combustion are usually: too high content of carbon in fly ash (called Loss on Ignition, LOI) and carbon monoxide. Other known negative effects include a drop of steam temperature and water wall wastage.

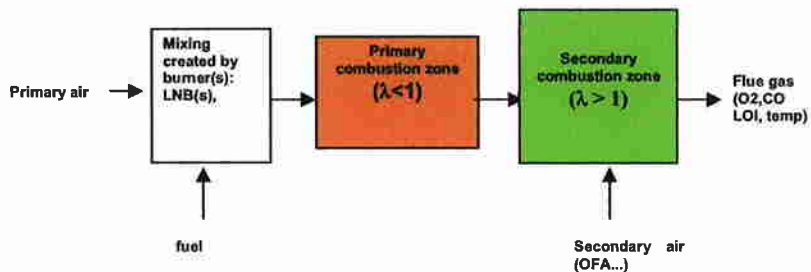


Figure 1. Conventional staged combustion concept

ROFA (Rotating Opposed Fired Air) is a boosted over-fire air system that includes a patented rotation process. With ROFA, the gas volume in the furnace is set in rotation via special asymmetrically placed high velocity air nozzles. ROFA promotes intensive internal recirculation of flue gases from the level of secondary air injection down to primary combustion zone. Combination of air staging and internal flue gas recirculation changes not only in-furnace flow

but also affects the combustion. Due to intensive recirculation and good mixing between secondary air and flue gas the combustion volume is larger than with conventional staged combustion. Such combustion is termed Volumetric Combustion System (Figure 2). The importance of extensive flue gas recirculation on combustion and formation of so called “flameless” combustion in industrial furnaces has been reported [2-5]. Volumetric combustion of gas and oil has also been reported [6-8] for conditions of highly preheated or oxygen enriched combustion air. With ROFA, volumetric combustion is created by very intensive mixing and recirculation of hot, reacting flue gases. Similar to “flameless” combustion, ROFA combustion is stabilized by the circulating temperature and flow field.

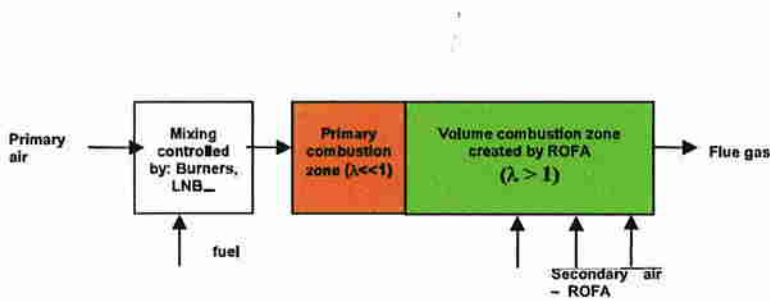


Figure 2. ROFA influence on staged combustion process creating Volumetric Combustion System

The ROFA technology directly affects combustion and NO formation. It allows deep staging, intensive internal flue gas recirculation, and efficient mixing between flue gases, fuel, and secondary air. The result of improved mixing is more uniform fuel distribution across the combustion volume. Pulverized coal combustion in a large combustion chamber is heavily dependent on mixing; therefore its intensification significantly improves coal combustion efficiency. High velocity turbulent air jets are source of kinetic energy introduced into the cross-flow of the flue gases high in the furnace. This kinetic energy, dissipated through the furnace, increases turbulence intensity of the flow and improves mixing.

Figure 3 shows turbulent kinetic energy change along a boiler furnace height. For the baseline case (without ROFA) the turbulent kinetic energy of the flow dissipates fast in the upper furnace above burners. There is a slight increase in kinetic energy in the upper furnace created by

the “nose” tip, but this is not sufficient for adequate mixing for traditional staged combustion. ROFA air jets dramatically increase kinetic energy, and turbulent mixing in the upper furnace. This promotes complete combustion and efficiently leads to the reduction of NO, SO₂ and Hg by means of special chemical additives and solid sorbents added into the upper furnace through the high velocity ROFA jets.

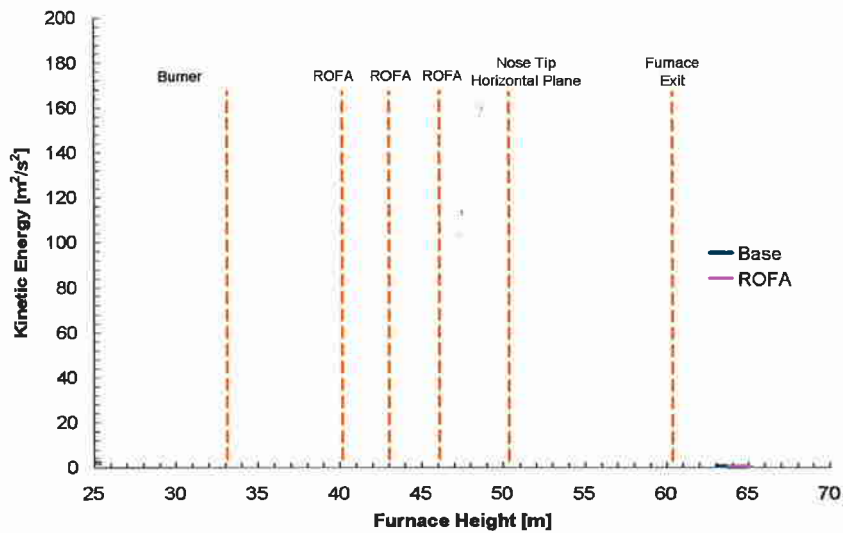


Figure 3. Mass-weighted turbulent kinetic energy changes, [9].

With ROFA the flue gas is well mixed with the available air in the entire upper furnace. This improves particle burnout. ROFA also increases particle residence time by changing their trajectories to utilize more of the furnace volume, thus reducing carbon content in the fly ash (LOI). The highly turbulent mixing and rotation prevent the formation of stratified flow, which enables the entire furnace volume to be used more effectively for the combustion process. Existence of the stratified flow, called also a “chimney” flow is a common phenomenon in conventional boilers. It is often accompanied by non-uniform and too high temperature and CO concentration at the upper furnace outlet. Application of ROFA changes the flow pattern of flue gases and eliminates these negative effects. More efficient mixing of the combustion air can also reduce the need for surplus excess air and also reduces CO emissions.

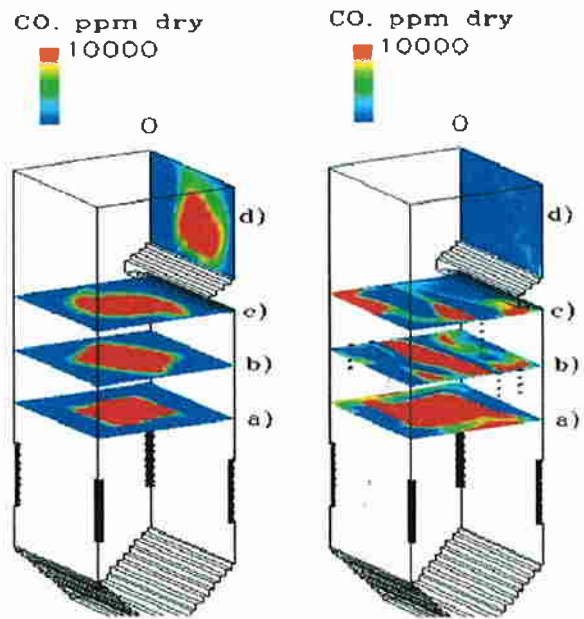


Figure 4. Carbon monoxide distribution: Left, before ROFA; Right, after ROFA.

Figure 4 shows CO distribution in coal fired boiler with tangentially placed low NO_x burners. High concentrations of CO are seen at the outlet from the upper furnace when ROFA is not applied (Figure 4). Characteristic distribution of CO with highest concentration in the middle is typical for tangentially fired boiler with so called “chimney” flow in the middle. Application of ROFA reduces CO dramatically at the outlet but also distributes CO more uniformly across whole volume of combustion. There is also a lack of the “chimney” flow. A conventional OFA system will have many low pressure nozzles and will stage the primary combustion air to 90-95% of the theoretical combustion air required. In a conventional OFA system, this small amount of staging occurs with high risk of corrosion, CO emission, and LOI increase.

The application of ROFA reduces the primary air to 70-80% of the theoretical air without creating corrosion, CO and LOI. Operation of the primary combustion zone at the deep sub-stoichiometric conditions (λ between 0.75 and 0.85) prevents oxidation of volatiles species (HCN, CN, CNO, NH₃, NH...) to NO. Instead, conversion of these species to N₂ is promoted. Control of oxygen level during first stage of pulverized coal combustion is a reason for very low conversion of fuel nitrogen into nitrogen oxide. Additionally uniform distribution and lower

levels of gas temperature and oxygen concentration in the upper furnace allow for better control of thermal-NO and NO formation during coal particles burning through volume combustion zone.

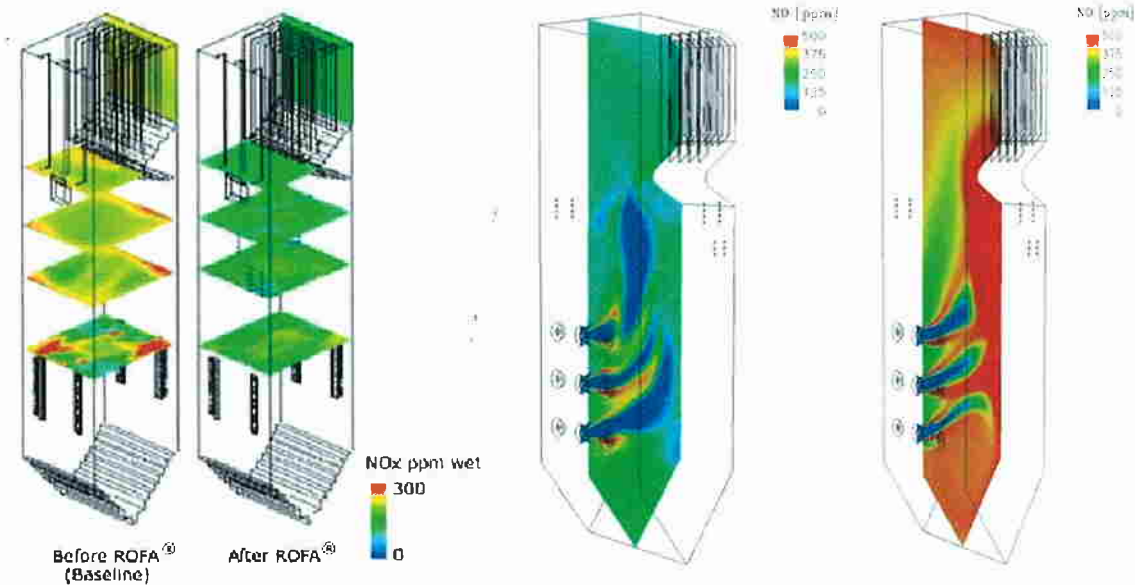


Figure 5. NO formation in tangentially coal fired boiler (with and without ROFA) and in coal wall fired boiler (with and without ROFA).

Influence of ROFA on NO_x formation for two most common types of firing configurations used in utility and district heating boilers is presented in Figure 5. Typically tangentially fired boilers generate less nitrogen oxides than wall fired units. Lower formation rate of nitrogen oxides in so called T-fired boilers results from better mixing efficiency in a rotating flow created by tangentially located burners. The same can be seen when ROFA is applied. ROFA applied in T-fired boilers results in higher NO_x reduction and higher combustion efficiency. Figure 5 shows influence of ROFA on fuel NO formation areas. It can be seen that in both cases NO formation areas were limited. It is particularly clear in case of wall fired boiler that combustion was moved towards the center of the combustion chamber when ROFA is in operation. Typical flame impingement on the opposite wall of the wall fired boiler was eliminated for the single-wall fired boiler case. As a result, slagging and wall corrosion was reduced and heat flux distribution uniformity was improved. In the case of the T-fired boiler a

uniform and low formation rate of NO_x, typical for volume combustion can be seen in Figure 5 (left side) as well.

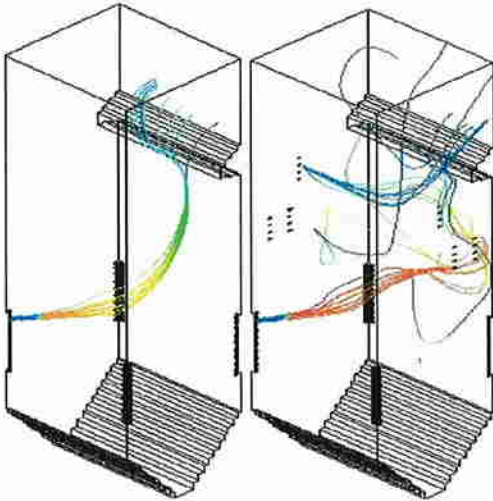


Figure 6. Particle and gas trajectories colored by carbon burnout in T-fired combustion chamber without (left Figure) and with ROFA (right Figure).

Figure 6 shows influence of ROFA on fuel particle trajectories colored by the carbon burnout in T-fired combustion chamber. Intensive kinetic energy added to the main flow of flue gas influence also movement of burning fuel particles. It is clear that with ROFA particles have longer residence time what helps to complete combustion (thus reduce LOI) in the existing volume of combustion chamber. Trajectories of secondary air molecules injected via ROFA nozzles show that mixing of air with reacting cross-flow occurs across the horizontal cross-section. It is also evidence on lack of the channeling flow in the middle of combustion chamber. The whole volume of the combustion chamber is used for the combustion process.

Analysis by computational fluid dynamics (CFD) presented in works [10-14] has been used to confirm and document the advantages of ROFA, including:

- less temperature variation in the volume of the furnace,
- even distribution of flue gas and increased residence time in the furnace, lowering CO levels and reducing excess air,
- increased particle and flue gas residence time and reduced LOI,

- less primary air and lower temperature thus less NO_x,
- increased primary combustion zone staging, further helping to reduce NO_x, and
- lower total excess air and complete combustion thus higher overall efficiency.

ROFA also stages the primary combustion air. Due to the high momentum of secondary air jets the ROFA ports can be located higher in the furnace than typical OFA systems. This creates the large volume combustion and a longer residence time in the furnace between the burners and the ROFA ports. Other OFA systems cannot provide the same long residence time without creating high CO or LOI problems downstream due to poor burnout. Economizer exit concentrations of CO are typically below 20 ppm for ROFA installations. For units with high LOI and CO emissions, ROFA installations further increase unit efficiency by promoting more complete burnout. The reduction of surplus excess air decreases the mass flow through the furnace (for the same firing rate), increases the heat absorption in the furnace, and results in less heat loss, which improves boiler efficiency.

ROFA system is generally applicable to most combustion chambers. Most applications reported already show that ROFA works well in pulverized coal fired utility boilers. However, there are also applications in grate fired boiler or bubbling fluidized bed boilers. In these two types of boilers ROFA is applied in the over bed section in order to promote mixing of the off bed gases and entrained solid particles. One of the last applications of ROFA shows that it works also effectively in CFB (circulating fluidized bed) boilers reducing sorbent consumption. Improvement of horizontal mixing in the freeboard of the CFB allows reduction of the calcium-to-sulfur (Ca/S) ratio to below 3.

Some ROFA installations use air from the FD fan outlet (upstream of the air heater) instead of the air heater outlet. This is called "ambient ROFA" and there is a heat rate penalty associated with this technique of the order of 1%. However, this can typically be countered by a reduced auxiliary fan load (smaller boost fan) and a reduced cost of installation due to smaller ducts and less insulation. In both hot and ambient ROFA configurations the mass flow through the boiler is typically lower due reduced excess air. Very good mixing allows often in practice to reduce total air excess number what results in some rise of boiler efficiency. Reduced mass flow through the boiler results in 1% to 2% increase in boiler heat transfer efficiency.

ROTAMIX

An extension of the ROFA concept is to use the optimal furnace conditions it creates as the platform for adding additives (chemicals, sorbents, and fuels) called Rotamix. Applying the Rotamix concept to well known processes like Selective Non Catalytic Reduction (Rotamix-SNCR) of NO_x, [15], Furnace Sorbent Injection (Rotamix-FSI) to reduce SO₂, and Reburning, can be realized more efficiently and more economically than in case of using traditional combustion staging concepts. Rotamix makes use of the well mixed flue gas and high velocity air to evenly distribute the additives into the flue gas. The high velocity air injection provided by ROFA creates the conditions for very effective mixing of additives with the combustion products in the furnace. The result is the efficient introduction of for example reducing chemicals directly into a well-distributed, rotating mixture.

For NO_x reduction, Rotamix-SNCR is tuned to adapt to changes in load and temperature in the furnace, and only introduces reducing chemicals to the furnace where the temperature most favors NO_x reduction. This reduces consumption of chemicals and lowers chemical slippage by increasing the reaction efficiency. Relative to other SNCR systems, the Rotamix-SNCR can decrease chemical costs. While NO_x reduction with typical low NO_x burners and OFA systems can sometimes exceed 50%, ROFA NO_x reduction routinely exceeds 60% and Rotamix-SNCR NO_x reductions exceed 35%. NO_x reduction achievable with the ROFA plus Rotamix-SNCR combination is often 75% or more. Rotamix can be used not only for urea, ammonia, or sorbent injection but also Hg control, [16]. ROFA/Rotamix is a multi-pollutant control technology because all the above mentioned options can be used together and in the same combustion chamber.

Another possibility is to combine SCR (selective catalytic reduction) with ROFA/Rotamix-SNCR. SCR-only and SCR-with-ROFA/Rotamix-SNCR can both achieve 90% NO_x reduction, but addition of the ROFA/Rotamix-SNCR reduces the impact of the following problems found with typical SCR systems: large catalyst costs, lack of NO_x reduction at low load operation, increased ammonia slip, high SO₂-to-SO₃ conversion, flue gas misdistribution, increased pressure drop due to SCR, and increased NO_x emissions when the SCR is out of-

service. The net result of employing ROFA/Rotamix SNCR with SCR is that NOx reductions of about 90% are achieved, but costs are significantly reduced.

Excessive sulfur trioxide (SO3) concentrations can adversely affect the operation of a power plant in various ways, including acid mist formation, significant air heater fouling/corrosion, and serious corrosion problems downstream of the air heater due to the formation of sulfuric acid. Reductions in SO3 of 70% to 90% have been shown at four ROFA installations, representing a large range of coal sulfur content. An additional 75% reduction in SO2 was achieved by injecting limestone sorbent.

FOSSIL FUELS FIRING EXPERIENCE

The first ROFA installation goes back to early 1990s and there are now more than 50 large scale industrial and power installations with ROFA and Rotamix operating in the USA, Asia, and Europe, including both fossil and biomass fired plants. In the USA a total of 20 fossil fired power plants have been successfully fitted with ROFA and Rotamix, at boiler sizes between 40 MWe and 590 MWe. Some examples are shown in Table 1.

Table 1. Rotating Opposed Fired Air and Rotamix installations versus NOx reduction

Unit name	Load MWe	NOx before mg/Nm3 (at 6% O2)	ROFA	Rotamix	NOx after mg/Nm3 (at 6% O2)	Reduction %	Firing config.
Cape Fear no. 5	155	719	Yes		313	56	T-fired
Cape Fear no. 5	155		Yes	Yes	197	73	T-fired
Cape Fear no. 6	175	719	Yes		325	55	T-fired
Cape Fear no. 6	175		Yes	Yes	209	71	T-fired
Bremo Bluff	175	561	Yes		280	50	Wall-fired
Coleman	160	742	Yes		300	60	Wall-fired
Vermilion no. 1	80	673	Yes		244	64	T-fired
Vermilion no. 1	80		Yes	Yes	150	78	T-fired

FOSSIL AND BIOMASS CO-FIRING EXPERIENCE

A recent development has been use of ROFA and Rotamix technology in a project to convert a pulverized coal fired steam boiler to operate on pulverized biomass. With conventional

combustion technologies such a conversion would be expected to encounter such difficulties as a fall in boiler efficiency, reduced steam production, drops in steam parameters, increased fouling and corrosion of heat transfer surfaces inside the boiler. Application of ROFA and Rotamix allowed a guaranteed reduction in all these negative effects, as well as NO_x reduction.

During 2005 such a biomass conversion was carried out on a 240 MWt, tangentially fired boiler in Helsingborg, Sweden at Västhamnsverket Power Plant - to our knowledge one of the first such projects in the world. In this case the steam production of 82 kg/s before the conversion was maintained, as well as all steam parameters. Before 100% conversion from coal to biomass was performed the boiler was converted gradually. First direct low percentage co-firing project was performed in 1998 and only 15% (energy basis) of biomass was used. After positive experience biomass share was increased to 30% in year 2000. High percentage co-firing at 70% of biomass was performed in the year 2004. During the years various types of biomass like wood residue, bark and straw were directly co-fired with coal. Since year 2006 the boiler is operated with 100% biomass and the plant is run with the same availability. Because of high content in biomass of alkali and chlor components the Rotamix system was installed in order to reduce fouling and corrosion risk.

Combustion process

Because of lower calorific value and density bigger amount of biomass must be burned to obtain the same effect. Large fraction of biomass is released as volatiles (up to 95% of mass) therefore gas phase temperature distribution along the boiler height will be different comparing to pulverized coal combustion. In case of dry wood pellets combustion a maximum temperature can be moved up towards convective heat transfer surfaces. It is known that there are substantial differences in composition of inorganic matter of biomass and coal. Because biomass has more silica, potassium than coal it reduces coal ash melting temperature. Co-firing thus creates higher flue gas temperature at the superheater level and lower ash melting temperature leading into slugging and corrosion (Figure 8).

Because there is substantial difference in amount and composition of volatiles coming from biomass and coal the combustion system must secure well controlled mixing. Modified combustion system must be flexible and secure complete combustion of volatiles as well as particulates. It is known common practice that introduction of direct and even moderate

percentage co-firing requires modification of air supply system. In case of large percentage amount of biomass the control of flow field and mixing is necessary especially if NO_x emission is to be controlled as well. ROFA by increasing volume of combustion (volumetric combustion) is able to mix very well large amount of volatiles released from biomass and therefore better control temperature distribution along the combustion chamber height. Controlling oxygen distribution and residence time ROFA can secure low NO_x combustion well as more complete combustion of biomass char particles.

Fuel handling and preparation

Wood biomass, delivered in form of wood pellets from Sweden and Canada was co-fired with Polish bituminous coal. Specific requirements for fuels preparation depend on the plant that plans to use biomass in co-firing. Taking into account requirements of the Västhamnsverket Power Plant some modifications and additions to fuel handling, processing, storage, and feed systems were gradually introduced when amount of biomass burned was increasing. Apart from revamping of transport lines, installing fire detectors, installing water sprayers the new mills for biomass pellets were installed. Size distribution of the wood pellets at delivery stage is shown in Table 2.

Table 2. Size distribution of wood pellets

Fraction (mm)	Weight%	Ack. Weight%
> 10.0	0.0	100.0
8.0 - 10.0	0.1	99.9
5.6 - 8.0	92.3	7.6
4.0 - 5.6	3.5	4.1
2.0 - 4.0	2.1	2.0
1.0 - 2.0	1.0	0.9
0.5 - 1.0	0.6	0.3
< 0.5	0.3	0.0

Because of different grindability of coal and biomass separate mills and transport lines were used. Three roller mills and two beater mills were used to pulverize wood pellets and coal. The plant was designed in such way that could operate fully on coal, coal and biomass or fully on biomass. When firing only coal the mills were operated below their rated output. When firing or co-firing biomass mills were operated at full rate and increased fuel feeder rates in order to

compensate for lower density and heating value of biomass. Size distribution of pulverized biomass is shown in Table 3.

Lower Heating Value of wood pellets is 20.6 MJ/kg (5.7 MWh/ton). Specific density was measured to be 736 kg/m³. Moisture content in pellets is low and equal to about 6.0 - 10% depending on operational conditions. Composition of dry wood pellets is: ash – 0.3%, sulfur - < 0.01%, chlor - < 0.01%, carbon – 51.4%, hydrogen – 6.1%, nitrogen - < 0.11%, oxygen – 42.1%. Mineral matter (dry substance) composition (in mg/kg) of used biomass was the following: Si – 38000, SiO₂ – 81000, Ca – 240 000, CaO – 340 000, Al – 7400, Al₂O₃ – 14000, Fe – 11000, Fe₂O₃ – 16000, K – 33000, K₂O – 40000, Mg – 58000, MgO – 97000, Mn – 25000, MnO₂ – 40000, Na – 5300, Na₂O – 7200, P – 11000, P₂O₅ – 25000, TiO₂ – 820. Very high amount of calcium and relatively high amount of potassium in the absence of sulfur indicates a high melting temperature.

Table 3. Size distribution of pulverized wood pellets

Particle size (mm)	rest on the sieve,%	After mill,%
2	0.0	100.0
1	7.7	92.3
0.5	23.9	68.4
0.25	25.6	42.7
0.15	15.4	27.4
< 0.15	27.4	0.0

Combustion system modification and performance

Originally the oil-fired boiler was in 1979 converted from oil to coal. In order to achieve the same boiler performance its height was increased make more combustion volume for coal combustion. A coal handling system with mills was installed. Combustion chamber was equipped with 12 burners to fire pulverized coal and 8 burners to fire oil in the corners (T-fired unit). The cross section of combustion chamber was 8.1 m by 7.6 m. The combustion chamber height was 24 m. Air staging in coal burners was done by transport air used as a primary air and secondary air without swirl. Construction and position of burners were kept before and after modernization the same and independently on co-firing ratio between coal and biomass.