Operating Experience from the World´s Largest Waste Fired Circulating Fluidized Bed Reactor in Västerås

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Valmet Power has a long experience in fluidized bed combustion. Since 1980’s both Bubbling Fluidized Bed (BFB) and Circulating Fluidized Bed (CFB) boilers have been used in combustion for various types of solid fuels, from fossil fuels to biomass and nowadays more and more for recovered fuels like demolition wood and SRF.

The design features for large scale CFB boiler concept for Waste-to-Energy is presented. Main design parameters of fuel mixtures, chemical as well as physical properties are described. Fuel based challenges in boiler operation, e.g. bed agglomeration, fouling, corrosion and flue gas emissions, and related process design and constructional features to tackle these challenges are discussed.

Early operating experiences of the 155 MW_{th} Mälarenergi Waste-to-Energy CFB boiler in Västerås, Sweden is discussed. This boiler is designed to burn household waste up to 70 percent and industrial waste up to 100 percent of heat input. Also some sludge, recovered wood, peat and biomass are part of the design fuel palette.

Waste Incineration

1. Introduction

Valmet has its own fluidized bed combustion technologies, BFB (called HYBEX) and CFB (called CYMIC), and is actively developing these technologies. In addition to combustion, CFB technology is also used in gasification of biomass and recycled fuels. Research Center in Tampere, Finland provides excellent possibilities for instance to test new fuels. There are three different sizes of test reactors for fuel testing, and the main focus during the last fifteen years has been in utilization of renewable fuels and opportunity fuels.

In Waste-to-Energy sector installed base of FBC boilers in Europe is about 11 pcs of CFB and 40 pcs of BFB boilers including all boiler suppliers. Many of those are located in Sweden, e.g. CFB boilers in Norrköping and Västerås and two BFB boilers in Borås.

The main benefits of the CFB combustion technology are fuel flexibility (e.g. wide heating value, ash and moisture content ranges), even – easily controllable combustion temperature, low flue gas emissions, high combustion efficiency with as low air coefficient (lambda) as 1.2 due to good mixing, and option for high steam parameters due to loopseal superheater possibility. Small size of fly ash particles after efficient cyclones is gaining benefit affecting low erosion rate in convection pass. These facts are valid also for Waste-to-Energy CFB solutions. For example wet municipal solid waste and very dry demolition wood can be used in the same boiler, only some crushing and big particle metal removal is required prior to combustor. Bottom ash is dry and usable metals can be easily separate for recycling purposes.

2. Circulating fluidized bed boiler – General arrangement

2.1. Main components of the CFB boiler

Key components in a CFB boiler are furnace, cyclone as a solids separator and loop seal. These together are forming so called hot loop. Nowadays the hot loop is typically part of the boiler surface as a membrane panel arrangement, connected to natural circulation evaporation loop. In the furnace, fluidization is maintained by primary air, which covers about 50 percent of combustion air. Primary air is fed through the furnace floor via fluidizing nozzles. Rest of the combustion air, secondary air and also fuel are fed to the lower part of the furnace. Fuel is fed either gravimetrically, pneumatically or by mechanical conveyors, depending on fuel palette and its properties.

Amount of bed material in the furnace is 30 tons in 150 MW boiler. Bed consist in the start-up of natural sand, sizing 100 to 500 microns, but during operation, fuel ash particles are forming main part of the bed material. Bed material escaping from the furnace together with flue gas is collected by cyclone and transported back to the furnace via loop seal. Due to circulating material, furnace temperature profile is quite even which is one of the main benefits of CFB combustion technology. Regardless of the fuel type, combustion temperature in hot loop is maintained in 800 to 950 °C, which is optimal for good combustion efficiency and primary emission control and minimizes fouling and slagging of heat surfaces. After cyclone, flue gas is passing through the convection pass and finally to flue gas cleaning and stack.

Fine part of the fuel ash is escaping with flue gas through the cyclone. Typical average particle size of the fly ash from CFB combustion is 20 to 40 microns and maximum size is close to 100 microns. Ash particles larger than that can be collected by cyclone and they are removed via bottom ash discharge openings in furnace floor together with some bed material. In biomass and recovered fuel combustion, bottom ash is typically sieved and suitable bed material fed back to the furnace by pneumatic transmitters. Magnetic metals can be easily separated from the bottom ash by magnet separators due to dry, sand like nature of bottom ash.

2.2. Suitable fuels for CFB combustion

In a CFB boiler, very wide range of solid fuels can be burnt. Also liquids and gases can be part of the fuel palette, but the main benefits are in combustion of challenging solid fuels and fuel mixtures. Typical fuels burnt in CFB boilers are: different type of coals, biomass and recycled fuels like demolition wood and SRF.

Basic fuel parameters in combustion are: heating value, moisture and ash content can vary a lot. As an example, fossil fuels from very low heating value, high ash coals (LHV_{wet} = 4,5 MJ/kg, ash content = 70 percent in dry solids) to high heating value pet coke (LHV_{wet} = 32 MJ/kg, ash content = 1 percent in dry solids) can be handled in a CFB boiler. However, those are not typically burnt in the same unit, even if it is possible from the design point of view. In biomass combustion fuel moisture can vary from as low as available up to 60 percent.

Due to good sulphur capture potential by in-furnace limestone injection, also high sulphur fuels like pet coke – 6 percent sulphur in dry solids – can be burnt without secondary flue gas cleaning equipment.

Suitable fuel particle size for the CFB combustion is below 10 to 20 mm for fossil fuels and below 200 to 300 mm for biomass and recycled fuels. Due to fuel feeding equipment and bed quality control, amount of large incombustible particles is limited to 5 to 10 w-%. That quality is maintained by crushing and screening equipment in fuel preparation plant.

2.3. CFB boiler size ranges

Typical size range for a CFB boiler is from 50 MW to 1000 MW fuel input. Also smaller and larger CFB boilers can be built, but typically other type of solutions are then economically more interesting. However, the fuel palette can be the main selection criteria in some cases out of that range to favour CFB technology. One example is waste coal which can be burnt feasible only in CFB boilers. Also Waste-to-Energy solutions might be favouring very high electricity production capacity and thus CFB for size as low as 20 MW fuel input.

3. Fuel related challenges and technical solutions

It is clear that mere fuel name is not an adequate variable to explicitly classify fuels, but the names can be used as basis for a simplified approach to obtain an overview of the main challenges. The following table summarizes typical main fuel groups and some of the phenomena that need to be tackled to achieve a good plant performance. The values in Table 1 indicate how demanding issues could be expected within different fuel groups compared to conventional fossil fuel case. Value 0 suggests that basic design could be applied without difficulties, value 1 requires more careful dimensioning, and value 2 indicates that most likely a dedicated solution is required for smooth operation. Some key items are discussed more in detail in the following chapter.

Table 1: Overview on the fuel specific issues

Challenge field	Fuel				
	Fossil	Wood	Agro	Recycled wood	SRF
High temp corrosion	0	0...1	1	1	2
Mid temp corrosion	0	0	0	2	2
Cold end corrosion	0	0...1	1	2	2
Superheater fouling	0...2	0...1	2	1	2
Cold end cleaning	0	0	1	1	1
Bed agglomeration	0...2	0...1	2	1	1
Loop agglomeration	0...2	0...1	2	0	1
High bottom ash/debris flow	0...2	0...1	1	1...2	2
High fly ash flow	0...2	0	0	1	1
Back pass erosion	1	0	0	1	2
Emissions	1	1	1	1	1

3.1. High temperature corrosion

High temperature corrosion is mostly related to chlorine compounds condensed on superheater tube surfaces. Corrosion caused by these compounds typically takes place in steam temperatures above 450 °C. Basic approaches of the methods to combat alkali chloride salts induced corrosion could be described as following:

- reduce concentration of alkali chloride vapors and aerosols in the vicinity of tube surfaces
- manipulate flue gas composition to a less corrosive composition
- reduce probability of contact between tube surface and molten/sticky phase chlorine compounds
- accept corrosion on selected heat surfaces

Examples of the first approach are locating finishing superheaters in the CFB loopseal, or utilizing an empty pass to cool down the flue gas and shift alkali chloride compound to less aggressive solid phase. In addition, superheater surfaces can be arranged to optimize the flue gas temperature in respect to the steam temperature.

Another method to reduce flue gas corrosivity is to manipulate chemical composition of flue gas by adding element sulfur or suitable sulfur compound in the fuel or flue gas. Target is to shift the balance of chlorine compounds from alkali to HCl.

The third approach is utilized for example in fluid bed heat exchangers with multi-layer tube construction (Figure 1) in order to increase the tube surface temperature above condensation point of the harmful compounds – typically in the range of 700 °C. The same principle is also used in recovered fuel cases, when the boiler steam pressure is limited in order to keep evaporating surface tube temperature below critical temperatures. Typically, steam pressures of 60 to 90 bar are used recovered fuel solutions.

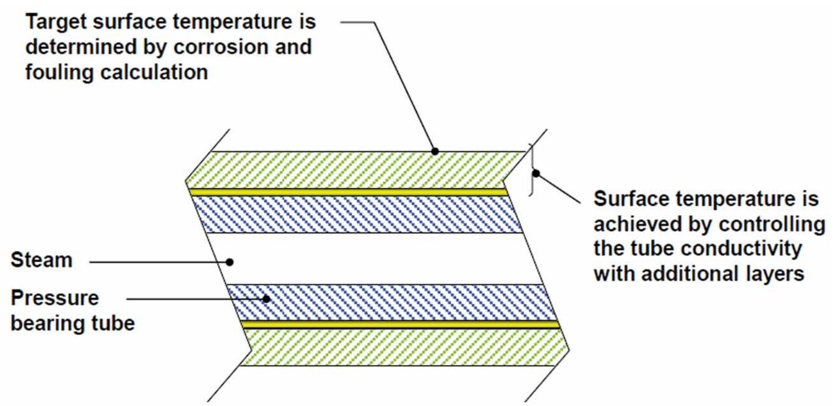

Figure 1: Multi layered tube construction of fluidized bed heat exchanger

In case of suitable fuel price differences, one practical method is to accept more rapid corrosion on some heat surfaces and utilize constructions and materials that facilitate economic exchange of the corroded surfaces.

3.2. Fouling

Fouling of the heating surfaces is caused by condensation of vapor phase compounds or solidification of sticky semi-molten ash particles on colder surfaces, such as boiler tubes or membrane walls. Excess fouling may create a problem for heat transfer or in worst case even a restriction for the flue gas flow through the convective pass.

There are several ways to avoid fouling problems. In CFBs, furnace and cyclone walls are naturally cleaned by bed material which is falling down close to the surface. Also compared to other boiler designs, maximum combustion temperature in a CFB is lower. Flue gas temperature after the cyclone is at maximum in the range of 900 to 950 °C. In optimized convection pass, appropriate values for design variables such as flue gas velocity, tube spacing, soot blowing type, location and frequency, must be selected.

For high ash flows with high melt portions, parallel design of tubing can be used, e.g. empty pass construction for recovered fuel designs.

3.3. Bed agglomeration and debris removal

Main factor affecting bed agglomeration is low melting point of fuel ash. This can be due to high content of K, Na, or P in biomass, especially in agro fuels, or high content of low melting point glass or metals such as Zn and Pb, together with Cl, in recovered fuels.

Methods to prevent agglomeration can be physical or chemical. There is still room for research in the field of chemical methods, but at least some Ca-based solids have been suggested as additives to reduce agglomeration tendency. Also selecting silica free bed material can be a solution in some cases.

Physically agglomeration can be avoided by diluting the bed with fresh inert make-up sand, utilizing bottom ash sieving and/or washing, or just adjusting the bed temperature low enough to prevent ash melting.

In recovered fuel combustion, an essential part of agglomeration abatement is effective removal of metal, glass and stone based impurities from the fuel. However, large quantities of these impurities end up even into the furnace. Dedicated designs in grid and loop seal floor are needed to secure even fluidization and effective debris removal, and to prevent presence of slow-moving bed particles and local hot spots.

4. Solid residue fuel concept

Solid recovered fuels are among the most challenging fuels. Typical for these fuels are high chlorine and heavy metal contents together with large amounts of incombustible debris. These fuels are prone to cause significant fouling, corrosion and in many cases combined corrosion-erosion. A dedicated SRF concept was developed to cope with these challenges. Special features of SRF concept are shown in Figure 2.

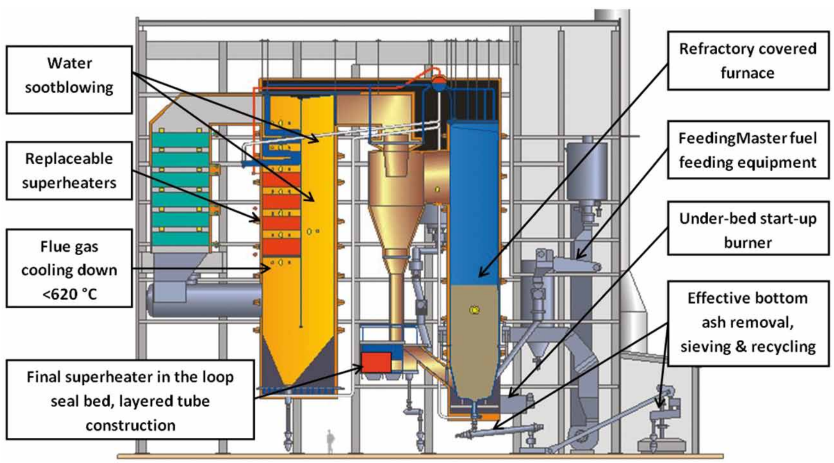

Figure 2: Special features of SRF concept

Basis of SRF concept is to meet residence time of 2 seconds at above 850 °C in the furnace as required by waste incineration directive – WID. Boilers of SRF concept are designed with extensive refractory lining to fulfill this requirement, typically within load range 60 to 100 percent depending on the heating value range of design fuels. Support burners are installed in the upper furnace to ensure meeting the residence time also during eventual disturbances. For start-up, under-bed start-up burners are applied to minimize bed agglomeration risk.

An apron-type dosing feeder – FeedingMaster – has been developed to facilitate controlled fuel flow even with demanding waste fuels. Large openings in fuel feeding and bottom ash system together with directionally blowing primary air nozzles and inclined floor construction are applied to ensure effective removal of metal debris from the furnace. Nozzle wear is minimized by careful material selection and by a stepwise nozzle arrangement to prevent nozzles blowing on each other. Bottom ash is sieved and the fine material is recycled back to furnace in order to keep needed make-up sand addition in low level. High availability is maintained by redundancy in design capacities of the fuel feeding and ash extraction devices.

The heat from the bottom ash, loopseal ash and boiler ash can be recovered by water cooled screws. In order to achieve high boiler efficiency, cooling water of screws can be cooled by combustion air heat exchangers connected to the closed cooling water system. Typically, flue gas air preheaters are not used.

To cope with chlorine and heavy metal corrosion, the boiler is equipped with water-cooled empty pass to reduce flue gas temperatures before convective superheaters. Metal coating is used in the upper part of the empty pass. Superheater corrosion is minimized by optimizing the locations of different superheater stages. The final superheaters with coaxial design are located in loopseal, protected from the most corrosive compounds in the flue gases. Easily replaceable tube banks are used in all superheater surfaces.

Fouling and erosion of the heating surfaces are minimized with adequately low flue gas temperature and design velocities. Soot blowing strategy includes water gun soot blowers in the empty pass and typically steam soot blowers at convective superheaters and economizers. Compared to other CFB concepts some extra tube shielding is used to protect back pass tube bundles. High efficiency cyclones prior to convection pass are maintaining fly ash particle size small and thus reducing erosion potential in CFB compared to other boiler technologies. Other benefits of high efficiency cyclones are already mentioned low primary emissions and high combustion efficiency as well.

5. SRF concept for the boiler in Mälarenergi

The experience gained from the SRF boilers delivered in the beginning of the millennium, together with continuous and extensive development work, have resulted advanced Waste-to-Energy CFB technology used in recent SRF boilers. Operating experiences from reference boilers have proven the high performance and reliability of selected SRF concept. Design basis of Mälarenergi boiler in Västerås, Sweden and operating experience with further improvements and development achievements are briefly discussed in the two following chapters.

5.1. Design basis of Mälarenergi boiler

Mälarenergi's Waste-to-Energy CFB boiler, is the world's largest recovered fuel fired boiler at the current time. The contract was signed in January 2012, erection started 10 month after that in November 2012. The hydro test was successful performed after 22 month in October 2013 and hot commissioning started in January 2014. The boiler was handed over to the client in September 2014 and is now in commercial operation since September 2014. The new boiler with a fuel input of 167 MW serves as a base unit to meet the disctrict heating power needs of Västerås and Hallstahammar municipalities. The boiler design steam parameters are 155 MW_{th}, 58 kg/s, 73 bar(g) and 470 °C. Boiler sideview is presented on Figure 3.

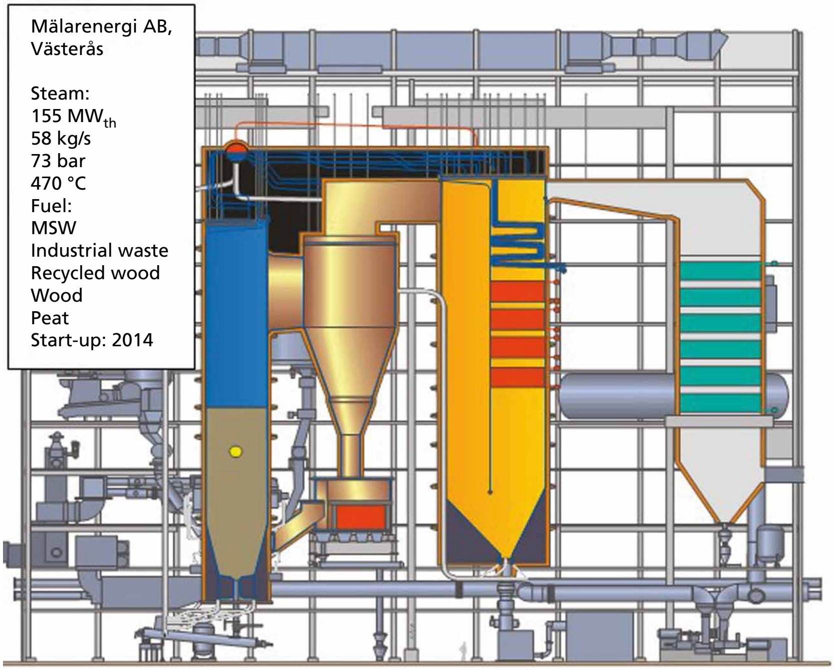

Figure 3: Sideview of world's largest recovered fuel fired boiler, Mälarenergi Unit 6

The new boiler in Unit 6 uses 60 tons of fuel per hour. Boiler is designed to burn household waste up to 70 percent and industrial waste up to 100 percent of heat input. In addition, sludge, recovered wood, peat and biomass are part of the design fuel palette. Design fuel properties and primary fuel design values are shown in Table 2 and Table 3.

Table 2: Fuel properties

Fuel	Moisture %	LHV MJ/kg	Ash w-% DS	% - LHV
Mixed industrial and municipal waste	18 to 47	8,5 to 16	< 25	0 to 100
Recycled wood	20 to 40	10 to 14	2 to 7	0 to 70
Biofuel mix	25 to 55	8 to 13	1,2 to 5	0 to 70
Crushed peat briquettes	13,5 to 21	14,4 to 17,3	12 to 16	0 to 30
Sewage sludge	70 to 80	0,7 to 1,2	40 to 50	0 to 4

	Unit	Design	Design range
Fuel			
• Industrial waste	% - LHV	70	0 to 100
• Household waste	% - LHV	30	0 to 70
• Sewage sludge	% - LHV	0	0 to 4
Moisture	w-%	41,8	18 to 47
Lower heating value (LHV), wet	MJ/kg	10	8,5 to 16
Sulphur, S	w-% DS	0,4	< 1
Chlorine, Cl	w-% DS	0,9	< 1,6
Ash	w-% DS	18	< 25

Table 3: Primary fuel design values

Primary fuel is a mixture of industrial waste and municipal solid waste. In addition, primary fuel mixture may include sewage sludge up to 4 percent of heat input. The secondary fuel consist of recycled wood, biofuels and crushed peat briquettes. The fuel feeding system consists of five separate lines – four for primary fuel and one for secondary fuel. Four FeedingMasters in a front wall ensure controlled and even primary fuel flow into the 15,1 m x 4,6 m furnace. Primary fuel feeding lines are dimensioned to obtain full load of boiler by three operating lines. Secondary fuel is distributed into both cyclone return ducts via frequency controlled metering screws and fuel chutes.

Fluidization behavior of grid and debris discharge capability with most challenging fuels are further enhanced by slightly modified grid construction and bottom ash hopper design together with control principle improvements related to bottom ash discharge. Also soot blowing method for economizers is selected to be steam soot blowers instead of sonic ones.

Bottom ash equipment is designed based on fuel flow, fuel properties and earlier operating experiences. The coarse material – bottom ash – is removed from the furnace through four bottom ash chutes. The heat from the bottom ash is recovered by water cooled screws, which are connected to boiler closed cooling water system. The circulating water is cooled via water coil air preheaters. Heat recovery from bottom ash to combustion air enables high boiler efficiency. Flue gas air preheaters are not used in this boiler.

5.2. Operating experience

In general the boiler could be operated in all areas of the combustion diagram without problems and is easy to operate (Figure 4).

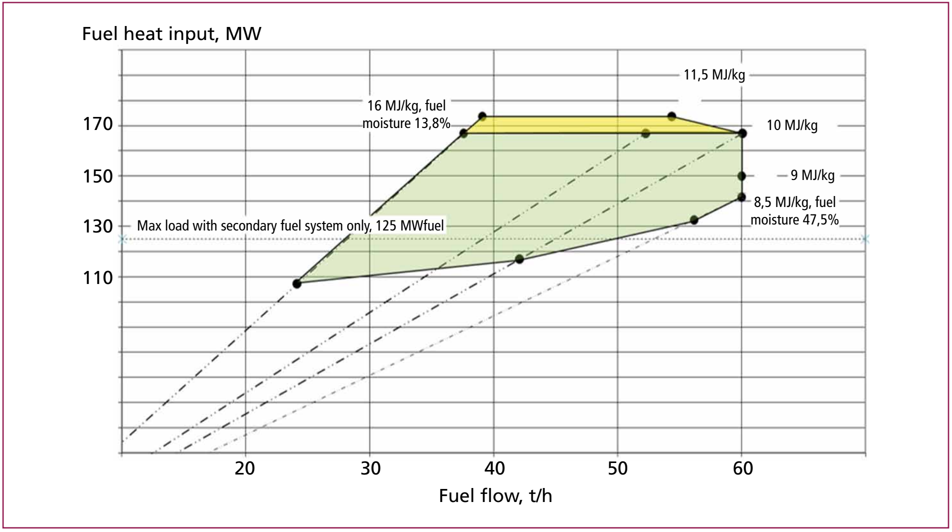

Figure 4: Combustion diagram of the plant

The good operational behavior reflect also the successful thermal dimensioning of the boiler as well as the reliable fuel feeding equipment that was used. A reliable and well controllable fuel feeding is essential in Waste-to-Energy boilers, due to the inhomogeneous waste fired.

The picture below shows an overview of the whole site including the fuel reception hall in the back and the boiler and flue gas treatment plant in the front of the picture.

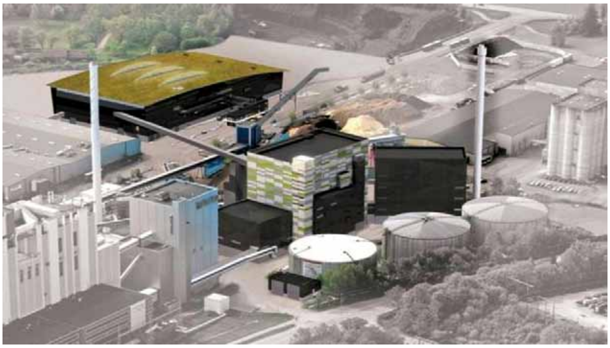

Figure 5:

Outside view of the fuel reception hall and the new boiler arrangement

The flue gas cleaning was not in the scope of delivery but the plant in total shows low emissions in line with the WID. Table 3 shows the emission values at the boiler outlet before the fuel gas cleaning.

Table 4: Granted emission values at the boiler outlet before FGT

Substance	Unit	Typical value
CO	mg/Nm^3	~ 0 to 5 (< 15)
NO_x (QAL, 30 min. avg.)	mg/Nm^3	< 45
SO_2	mg/Nm^3	~ 0
HCl	mg/Nm^3	~ 750
TOC (QAL, 30 min. avg.)	mg/Nm^3	~ 0 to 5
NH_3	mg/Nm^3	~ 0
O_2, wet (after boiler)	%	~ 4

During the operation issues due to the quality of the fuel were encountered. The extremely high glass content – even >10 percent ds. and high aluminium content as well as high amount of non-fluidisable material caused blockages in the bottom ash chutes. This were encountered on a regular basis when the fuel glass content was extremely high. As a result the ash discharge operating parameters were tuned for high glass content fuel that decreased the discharge problems, however still some modification were needed on the bottom ash equipment in order to increase bottom ash discharge capacity to meet actual fuel requirements. After these modifications the bottom ash system was working as expected.

Another problem were the higher deposit rate in the empty pass of the boiler which was caused by the fuel quality with high aluminum and glass content and inadequate water sootblowing frequency. The higher deposition rate in the pass also caused some blockage in the hopper discharge system.

Other challenges encountered during the commissioning were the dust content in the bottom ash room. This was partly related to fuel quality, due to the higher bottom ash discharge rate, which was about double of the design value. In addition, the vibrating sieves were not gas-tight, and fine dust was leaking through various holes of the structure. Therefore these were replaced with drum sieves that solved also this issue. The under pressure system was inadequate designed which could be solved with the installation of an additional fan to increase under pressure in the bottom ash equipment. All these measures solved the dust problem in the bottom ash area.

Challenges were also encountered with the under bed start-up oil burner and duct. The duct heat resistant plates overheated due to too narrow duct dimensions and higher local heat of burner flame than it was expected as well as uneven primary air flow distribution before burners and the flame shape of the burners and poor function of dampers. By tuning the burners and installation of refractory lining into the burner duct – section of primary air duct between burners and windbox – as well as improvement of the control logics these issues were successfully solved.

Obviously, major problems have been related to bottom ash discharge – due to poor quality of waste fuel. Fuel quality has improved a lot during last ~ 4 to 6 months which also helped to decrease the amount of bed ash discharge. At the moment there are no bottom ash discharge related problems if glass content is in reasonable level. In order to better understand the impact of the fuel on the boiler behavior an extensive fuel quality evaluation program was established with these main targets:

- More knowledge for process control/adjustments; optimized operating parameters based on fuel quality
- Improved boiler operation and availability; problems and risks related to fuel quality fluctuations can be minimized
- Better prediction of needed maintenance
- Possibility for fuel quality improvements/fuel selection

6. Conclusions

Circulating Fluidized Bed (CFB) boilers have been used in combustion for various types of solid fuels, from fossil fuels to biomass and nowadays more and more for recovered fuels like demolition wood and SRF. The main benefits of the CFB combustion technology are fuel flexibility, low flue gas emissions and high combustion efficiency. These facts are valid also for Waste-to-Energy CFB solutions.

Increasing interest in the use of renewable energy generated by means of locally acquired bio masses and recovered fuel brings new challenges to power boiler design. If the fuel selection includes more of the demanding fractions, several dedicated solutions are required to combat increasing practical challenges. Boiler concept for demanding fuels includes typically features such as loopseal superheater with layered tube design, easily exchangeable super heater surfaces also in convection pass, robust fuel feeding and ash discharge equipment, and more sophisticated flue gas cleaning system. Long experience in SRF combustion together with continuous and extensive development work, have resulted advanced Waste-to-Energy CFB technology. High performance and reliability are the cornerstones in SRF concept covering the size range from 50 to 250 MW_{th}. As high as 520 °C superheating steam temperature capability in full waste combustion is now possible due to state-of-the-art loopseal construction and layered tube final superheater design.

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