COMPARISON OF ASHES AND DEPOSITS OBTAINED BY RDF COMBUSTION IN A BF-BOILER APPLYING DIFFERENT BED TEMPERATURES

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ABSTRACT

Chemical fractionation and SEM-EDX was used for characterisation of ashes and deposits from different combustion tests in a commercial 20 MW bubbling fluidized bed (BFB) boiler. The fuel combusted was a mix of sorted MSW (Municipal Solid Waste) and industrial waste often referred to as RDF (Refuse Derived Fuel) mostly containing combustible material as paper, plastics and wood. This fuel type often contains a lot of alkali and chlorine and is therefore considered as a risk fuel prone to cause bed agglomeration, deposit formation and corrosion.

In order to investigate the impact of the bed temperature on the alkali and chlorine distribution in the boiler combustion tests were performed. The bed temperature for this boiler is designed to be in the range 850-900°C. In this investigation however the bed temperature was reduced to 700-750°C. Two deposit probes, each carrying two rings made of high alloy steel, were used for collection of deposits during combustion. In addition, samples taken on the bed ash, return sand, return shaft ash, cyclone ash and textile filter ash were analysed.

By reducing the bed temperature the need for fresh bed sand was reduced and the fly ash flow decreased. In addition, the agglomerates found in the tests with the normal bed temperature disappeared totally when the bed temperature was reduced. The deposits formed on the bed ash and on the return sand particles were found to consist of compounds with melting temperatures between 675 and 801°C, which could explain the difference in agglomeration tendency.

Keywords: reduced bed temperature, RDF, alkali, agglomeration, deposit formation, BFB

1. INTRODUCTION

The combustion of different waste fractions for heat and power production is increasing all over the world. However, these fuels often contain high concentrations of alkali and chlorine having both low melting and vaporisation temperatures making the combustion demanding [1]. Various additives, e.g. kaolin and sulphur in different compounds are able to ease the boiler operation, given their ability to capture alkali metals [2-4]. Fluidized bed (FB) boilers are known to be very fuel flexible but as the combustion takes place in a sand bed, chemical reactions between the sand bed particles and the inorganic compounds in the fuel may occur. These reactions often lead to the formation of eutectic melts causing bed agglomeration and in the worst case total defluidization. The bed temperature in FB boilers is typically 780-900°C, controlled within a range of a few degrees centigrade [5].

High alkali and chlorine concentrations in the flue gas together with high temperature pressure vessel parts will cause high temperature corrosion, e.g. on the super heater tubes [6]. Therefore, waste combustors are designed for low steam temperatures to avoid severe corrosion, typically 400 °C in grate boilers and BFB boilers and up to 450 °C in CFB boilers. Consequently the electric power output is lower than from boilers burning fossil fuels. A reduction of the alkali chlorides in the superheater region could enable for a higher steam temperature and thus increased electric efficiency of the boiler.

This project investigated the possibility to capture alkali and chlorine in the bed ash by reducing the bed temperature by approximately 150°C. A pre-study was made to confirm the possibility of a temperature reduction in the current boiler by means of its existing equipment [7].

2. EXPERIMENTAL SECTION

2.1 The fuels

The fuel used was a mixture of 70% sorted industrial waste and 30% sorted household waste. It was pre-treated in a waste treatment plant and sorted into the fractions; combustibles, compostable and metals. The combustible fraction, mainly consisting of paper, plastics and wood, is crushed and shredded by a hammer mill into smaller pieces with a size of approximately 10*10 cm.

2.2 The boilers

The two twin 20 MW_{th} bubbling fluidized bed (BFB) boilers at Ryaverket (Borås, Sweden) were used for the combustion tests. The boilers which are parallel but separate units, sharing the fuel feed and ash transportation system, are producing superheated steam with a temperature of 405°C and 49 bars pressure. Boiler number 1 is equipped for research purposes, e.g. with measurement openings in a number of locations in the walls and sampling equipments for the solid flows. Also boiler number 2 is equipped with some measurement hatches. Because of the shared fuel and ash system both boilers were kept at the same temperature during the combustion tests.

2.3 The tests

To guarantee no memory effects from the previous combustion tests the boilers were run at the actual bed temperature for three days prior to each measurement. In the reference case (Ref) the boilers were run with the bed temperature 870°C, i.e. the normal value. In the reduced bed temperature case (RBT) the temperature was reduced to approximately 720°C by means of flue gas recirculation and water spraying on the fuel.
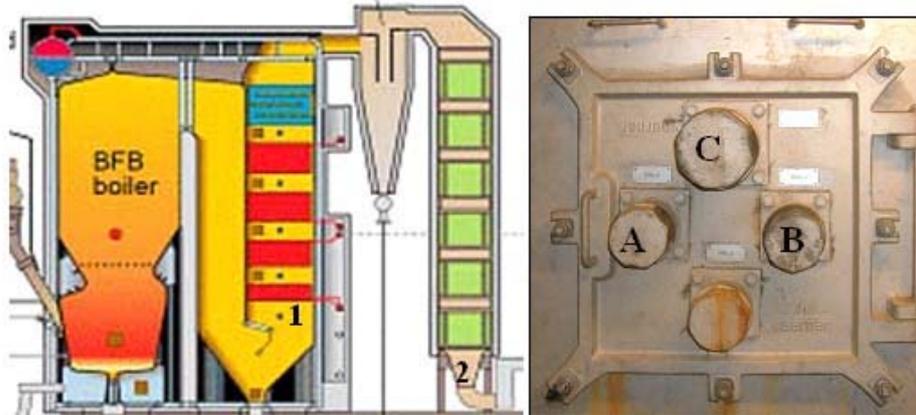

Figure 1: a) The different measurement positions 1: deposit probes and pyrometer upstream the super heaters 2: Sampling to determine HCl and SO$_2$ in flue gas downstream economiser b) Measurement hole A and B: deposit probe C: pyrometer.

In the combustion experiments two deposit probes with different surface temperature were inserted in front of the convection pass for sampling of depositions, Figure 1a. The material temperatures of the probes were, respectively, 435°C and 500°C. The lower temperature corresponding to the current steam data of the boilers and the higher is simulating an increased steam temperature. The probes were equipped with two deposit rings each (Figure 2), one for element analysis and one for SEM-EDX analysis. Each ring was carefully weighed before and after sampling. The deposit probes were exposed in the boiler during two hours in each sampling. The samplings were repeated two times changing position between A and B, see Figure 1b. The distance between the measurement positions A and B are around 0.2 meters. Samples from the bottom ash, return sand, cyclone ash, return shaft ash and textile filter ashes were taken during the combustion tests and analysed.

Figure 2: Deposit probes with sampling rings used in the combustion tests.

To investigate if the lowered bed temperature affected the flue gas temperature in the convection path a suction pyrometer was inserted in front of the super heaters, measurement hole C, Figure 1b.

2.3.1 Flue gas analysis

The flue gas from the combustion were continuously analysed by a FTIR (Fourier Transform Infra-Red spectrometry), which measures H_2O, CO_2, SO_2, CO, NOx, HCl, NH_3, and N_2O. Also, HCl and SO_2 in gas phase were sampled downstream of the economiser (no 2 in Figure 1a) by means of a wet chemical analysis [8]. A measured volume of the flue gas was sucked through a heated glass probe and bubbled through a solvent of 0.1 M NaOH(aq) and 0.3% H_2O_2 capturing HCl and SO_2. The sampling was performed during 2 hours.

2.3.2 Chemical fractionation

Chemical fractionation was carried out on the samples of fuel, bottom ash, return sand, return shaft ash and cyclone ash, in accordance with the metohod described by Pettersson et al. [9]. It is a step by step leaching method resulting in selective extraction of inorganic elements, based on the solubility of their association forms in the fuels and ashes. The experimental procedure consists of three successive extractions but in this work only two steps were used, with H_2O and NH_4Ac, because only water soluble salts and ammonium soluble ion exchangeable elements were of interest. The acid soluble compounds in addition to minerals in the ashes and fuels were analysed as a solid rest fraction

2.3.3 Analytical methods

Leachates and solid samples were analysed for Ca, Al, Fe, K, Mg, Na, P, Si, S, Cl, Ba and Ti using Inductive Coupled Plasma with an Atomic Emission Spectroscopy detector (ICP-AES) or a Mass Spectrometer detector (ICP-MS). All solid samples were totally dissolved according to Swedish standards, SS028311 and SS028150-2. The minor elements were analysed by ASTM D 3683.

2.3.4 SEM-EDX

The topology of ash particles as well as of the deposits on the deposit rings were examined by Scanning Electron Microscopy (SEM). In addition, the distribution of key elements in the sample structures was examined using Energy Dispersive X-ray Fluorescence spectrometry (EDX). The fact that each element has a unique atomic structure, therefore emitting different energy X-rays allows for elemental analysis of the specimen. Since characteristic X-rays could provide two types of information, identifying the composition of the sample and also the abundance of the elements in the sample.
In this work both high-vacuum and low-vacuum (environmental SEM and ESEM) electron microscopes were used. The ESEM option gives the advantage that susceptible and non-conducting materials can be examined without damaging the sample material. The specimen is mounted in epoxy or by spreading on a carbon adhesive tape or as in case of deposit rings analysed directly on the surface of the steel ring. No covering by conducting material is needed. The charge build up on the sample surface is removed by a small injection of water vapour using the low vacuum mode in the microscope.

2.3.5 **XRD**

X-Ray Diffraction (XRD) was used to determine the crystalline elements in the ash fractions. The equipment used in this work is a powder diffractometer Siemens D5000, X-ray tube with Cu characteristic radiation with wavelength 1.54 Å and scintillations detector. Data was collected in the 2theta region 10-70 degrees. The detection of possible crystalline compounds (detection limit 1 to 2 wt-%) was made by the help of JCPDS data base version 2010.

3. RESULTS AND DISCUSSION

3.1 Fuel analysis

Table 1: Fuel analysis

Fuel analysis	Ref	RBT
Moist, raw, Wt-%	33.1	35.7
Ash, dry, Wt-%	18	19
Dry sample, Wt-%		
S	0.2	0.35
Cl	0.47	0.49
C	46	46
H	6.1	6
N	1.1	1.1
O (diff)	28	27
LVH, raw, MJ/kg	11.6	10.9
HHV, dry, MJ/kg	18.6	18.4
Ash analysis, g/kg		
Al	11	11
Ca	26	27
Fe	4.7	9.8
K	4.4	3.6
Mg	2.9	3.1
Na	6.4	8.1
P	2.1	1.4
Si	35	45
Ti	2.3	2.5
Trace elements, dry, mg/kg		
As	13	29
Cd	1	0.4
Pb	120	120
Cu	1200	960
Cr	100	110
Ni	16	22
Zn	530	600

The fuel analysis showed that there were no large differences in fuel composition between the two combustion tests, Table 1. The element with the largest disparity is S which is found in higher concentrations in the RBT case compared with the Ref case. Because of the size of the boilers and the type of fuel, research with exactly the same fuel composition is impossible to achieve. The concentrations of total alkali, Cl, Al and Ca in the fuel, which are important in deposit formation and agglomeration, were found in equal amounts during the two tests.

3.2 Flue gas composition

Table 2 shows the flue gas measurements of HCl and SO_2 downstream the economiser together with operating parameters. The HCl concentration increased with 25% in the flue gas in the RBT case. In addition, the FTIR measurements after the textile filter show an increase of HCl by 36%. Unfortunately, the bed temperature increased from 695°C to 755°C during the measurements in the RBT-case which could have caused a release of Cl captured in the bed. However, the HCl concentration in the flue gas should also increase as a result of the increased alkali capture in the bed. Even SO_2 increased some downstream the economiser but due to the higher concentration in the fuel in the RBT case the reason of this increase is more uncertain.

Table 2: Measured SO₂ and HCl (recalculated for 11% O₂) some of the operational parameters during sampling.

		Ref Mean	Min	Max	RBT Mean	Min	Max
T_{bed}	°C	874	870	883	725	694	754
O_2	vol.-%	7.3	7.0	7.7	6.1	6.0	6.2
CO	mg/Nm³, dg. 11% O_2	6.0	5.0	9.0	13	8.0	19
H_2O	vol.-%	13	13	14	16	16	17
Total air	Nm³/s	8.3	8.0	8.5	7.3	7.0	7.4
FGR	Nm³/s	4.4	3.9	4.9	4.0	4.0	4.0
HCl	mg/Nm³, dg. 11% O_2	530			660		
SO_2	mg/Nm³, dg. 11% O_2	114			111		

FGR = Flue Gas Recirculation

3.3 Ash composition and element distribution

During the combustion tests with reduced bed temperature all ash flows was reduced, except the bed ash flow that increased. Table 3 shows that Cl was found in higher concentration in the bed ash, return sand and return shaft ash in the RBT case compared to the Ref case. However, the Cl concentration was reduced in the cyclone and filter ash.

The Al concentrations decreased somewhat in the bed ash and return sand in the RBT case and thus increased in the other ash fractions. No significant changes were seen in the Ca, P and Si distribution. Fe increased some in most ashes in the RBT case probably only due to the higher concentration in the fuel. The total alkali input with the fuel was almost the same in the two cases but the distribution between K and Na varied. There were some variations in the ashes as well, but the difference in total alkali in the three coarser ashes was small. However, in the RBT case both K and Na were reduced in the cyclone ash and increased in the filter ash. The concentration of S was higher in all ash fractions in the RBT case, which correlates well with the higher S input flow with the fuel in this case,

Table 3: Analysis of the five ash streams.

Sample Main element [g/kg DS]	Bed ash Ref	RBT	Return sand Ref	RBT	R. shaft ash Ref	RBT	Cyclone Ref	RBT	Textile filter Ref	RBT
Cl	0.3	0.8	0.4	2.4	1.5	1.8	22	20	170	142
Al	63	55	65	59	68	70	100	112	16	21
Ca	63	59	70	86	53	71	160	159	325	313
Fe	15	16	17	24	25	31	28	31	7.9	7.9
K	24	19	24	22	23	20	15	12	1.8	3.0
Mg	9	9.1	6.3	7.4	7.4	9.2	19	20	7.3	9.9
Na	42	50	30	30	24	27	23	22	13	15
P	1.7	1.4	1.7	2.5	3.1	3.1	6.2	6.1	2.5	4.2
Si	312	302	304	277	316	295	171	162	28	32
S	1.3	2.6	1.4	9.1	3.4	6.6	13	17	15	16
Ti	4.5	2.8	6.6	8.1	5.3	6.3	16	17	7	9.8
Trace elements [mg/kg DS]										
As	46	23	65	49	20	32	34	30	77	48
Cd	1	1	1	1	1	1	6	9	65	49
Co	14	18	8	14	8	6	42	32	6	11
Cr	320	230	420	600	200	270	330	520	230	330
Cu	4300	5600	1800	2000	6100	4700	3500	5000	6600	7500
Mo	20	24	22	23	20	20	22	22	16	19
Ni	52	180	66	120	90	110	140	160	46	67
Pb	1300	730	920	380	340	500	670	1000	3700	3400
V	40	40	36	40	36	38	55	60	20	29
Zn	3000	2500	3100	2500	2700	2900	5500	7500	4600	5200
Sb	190	76	300	350	120	130	210	200	440	400

Table 1. Element balances over the boiler showed that the increase of sulphur was larger in the bed ash and return shaft ash than in the cyclone and filter ash.

Most of the trace elements did not show any clear trend in their distribution. However, the concentration of Cu was reduced in the return shaft ash and increased in all other ash fractions and Ni was found in higher concentrations in all ashes in the RBT case. Both Pb and Zn were found in lower concentrations in bed ash and return sand and increased in return shaft and cyclone.

3.3.1 **Fractionations of fuels and ashes**

The fractionation results show that as much as 30% of the Cl input with the fuel in the Ref case and 40% in the RBT case was neither soluble in H_2O nor in NH_4Ac. Hence, this Cl was incorporated in plastics, minerals etc. A small fraction of Cl was also found in the solid residue from the fractionation of the bed ash, return sand and return shaft ash in the Ref case but not in the RBT case, Table 4. The bed ash, return sand and return shaft ash in the RBT case had higher concentrations of Cl and S than the Ref case. S was dissolved by 70-100% in all samples. The largest difference in dissolved Cl and S were found in the return sand leachates where five times and seven times more dissolved Cl and S respectively were found in the RBT case compared to the Ref case, see Figure 3. Since just the deposit layer

Table 4: Chemical fractionation results of the bed ash, return sand, return shaft and cyclone ash.

		Bed ash mg kg⁻¹ TS	H2O mg kg⁻¹ TS	NH4Ac mg kg⁻¹ TS	Solid Rest mg kg⁻¹ TS	Return shaft ash mg kg⁻¹ TS	H2O mg kg⁻¹ TS	NH4Ac mg kg⁻¹ T	Solid Rest mg kg⁻¹ T
Cl	Ref	300	61	446	663	1500	1210	362	249
	SBT	800	697	597	0	1800	1472	1403	0
Al	Ref	62800	107	0	48814	68300	679	1	52733
	SBT	55200	27	0	45250	70100	350	3	58276
Fe	Ref	14900	0	0	25333	24600	0	0	21055
	SBT	15800	0	1	54088	30800	0	0	25236
K	Ref	23800	23	54	20461	23000	484	74	21055
	SBT	19300	184	158	18700	19900	764	118	16264
Mg	Ref	8800	0	446	6918	7400	0	1142	5359
	SBT	9100	0	491	7131	9200	0	1348	6361
Na	Ref	41700	31	77	31179	24200	717	125	19141
	SBT	50200	406	134	42949	27000	1196	219	20732
P	Ref	1700	0	36	1169	3100	0	31	2393
	SBT	1400	0	9	1609	3100	0	13	2830
Si	Ref	312000	57	607	243875	316000	5	217	258687
	SBT	302000	60	448	252834	295000	12	33	247167
S	Ref	1300	66	679	0	3400	279	2537	0
	SBT	2600	464	1237	255	6600	359	6376	572
Ca	Ref	62500	497	12320	36050	53300	931	17577	28711
	SBT	58600	755	6825	40971	71000	589	27327	37031

		Return sand mg kg⁻¹ TS	H2O mg kg⁻¹ TS	NH4Ac mg kg⁻¹ TS	Solid Rest mg kg⁻¹ TS	Cyclone ash mg kg⁻¹ TS	H2O mg kg⁻¹ TS	NH4Ac mg kg⁻¹ T	Solid Rest mg kg⁻¹ T
Cl	Ref	400	112	929	1140	21800	20879	1747	171
	SBT	2400	1804	3518	0	20100	15513	2045	0
Al	Ref	64900	61	0	54243	99700	47	37	80679
	SBT	58800	294	0	46231	112000	2	45	50747
Fe	Ref	17300	0	0	15200	28400	0	0	24870
	SBT	23600	1	0	20517	30900	0	0	19852
K	Ref	23600	89	72	22799	15300	4448	223	12051
	SBT	21500	427	98	18553	12100	3285	335	7969
Mg	Ref	6300	0	1394	4275	18900	0	3530	13760
	SBT	7400	0	1148	5817	19700	5	3161	9684
Na	Ref	29800	29	137	24699	22800	3994	334	13760
	SBT	30000	826	463	23198	22300	3741	390	9995
P	Ref	1700	0	12	1615	6200	0	6	5897
	SBT	2500	0	0	2673	6100	0	0	2942
Si	Ref	304000	112	1187	247278	171000	24	13	137256
	SBT	277000	9	667	242628	162000	78	0	112800
S	Ref	1400	34	1239	0	13400	300	13564	1538
	SBT	9100	237	8147	1875	17200	1551	14131	2267
Ca	Ref	70300	601	28394	37999	160000	7989	61316	85806
	SBT	85800	788	37033	47017	159000	6570	59498	46037

on the sand particles in this fraction is dissolved by these solvents the results indicates an enrichment of Cl and S in this deposit layer. Na, K and Mg were just dissolved by 5% in all samples, but also for K and Na the difference in dissolved concentration were largest for the return sand samples. The element that was found in highest concentrations in the leachates was Ca which together with Si also was found in highest concentrations in all the ashes.
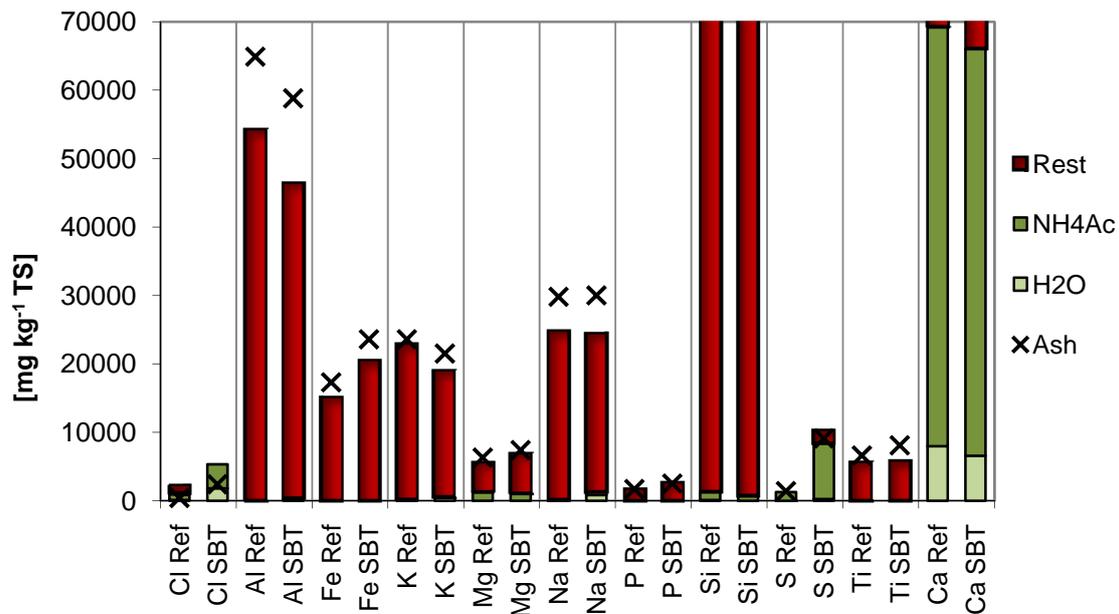

Figure 3: Chemical fractionation results of the Return sand in the Ref and RBT case. The bars representing concentrations found in the leachates and solid rest and X representing concentration in the original sample.

3.3.2 **SEM-EDX analysis on ashes**

Differences in the ash formation were visible by ocular inspection in the bed ash and return sand. The ash particles in the RBT case had a more white deposit layer on their surfaces than in the Ref case and no agglomerates were found in these ashes. The bed ash from the RBT case contained a lot of glass pieces, which were not seen in the bed ash from the Ref case. Both the bed ash and return sand from the Ref case contained a lot of agglomerates of different sizes. Analyses showed that many of the larger agglomerates ($2cm^2$-$5cm^2$ in size) had a core of molten glass in the centre surrounded by smaller ash and sand particles. This explains why no unmolten glass pieces were found in this ash and that the deposit layer on the particles in the bed ash and return sand were more transparent than in the Ref case.

All five ash streams were analysed by SEM-EDX. The cyclone and filter ash were mounted on a sticky coal film whereas the coarser bed ash, return sand and return shaft ash particles were immersed in epoxy, ground and polished exposing the cross section of the particles. The deposit layer on the particles was most clearly seen in the return sand samples, Figures 4 and 5.
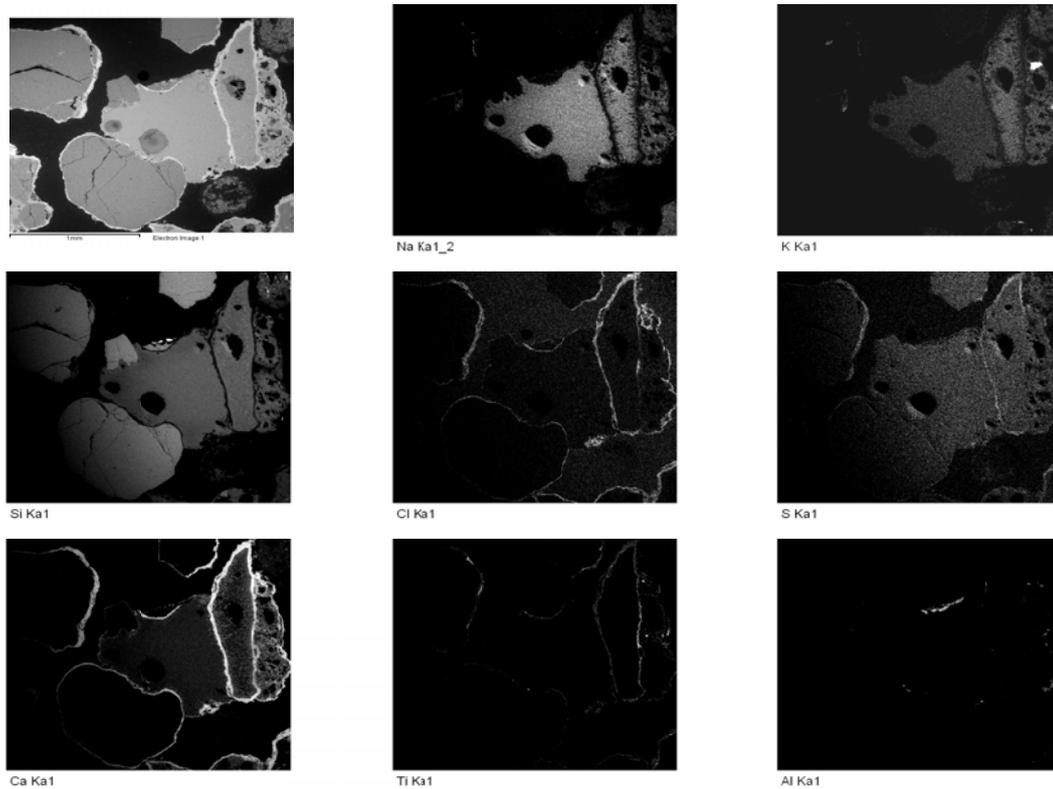
Figure 4: Return sand, Ref case, SEM photo (upper left) and EDX mapping on the cross section of the sample. Analyses of the elements Na, K, Si, Cl, S, Ca, Ti and Al.

EDX element analysis of the deposit layers on the particles in the two cases showed no large differences in the element composition. There were a few percent more Cl, S, Mg and Al found in the deposits from the RBT case and a small reduction in the Si concentration. This gives no explanation of the difference in agglomeration behavior in the two cases. However, most likely there are $CaCl_2$, NaCl and KCl present in the deposits having the melting temperatures 782°C, 801°C and 770°C respectively [1] which would cause the formation of molten eutectic compounds in the Ref case but not in the RBT case. Also some alkali silicates have melting temperature as low as 700°C, whereas alkali aluminium silicates have melting temperatures around 1200°C. The return sand particles in both cases consisted of SiO_2, alkali silicates and alkali aluminium silicates, the last one mostly found in the RBT case.

The analyses of the bed ash resembled those of the return sand. Even the return shaft ash correlated well with the return sand with the difference that no agglomerates were found in none of these ashes.
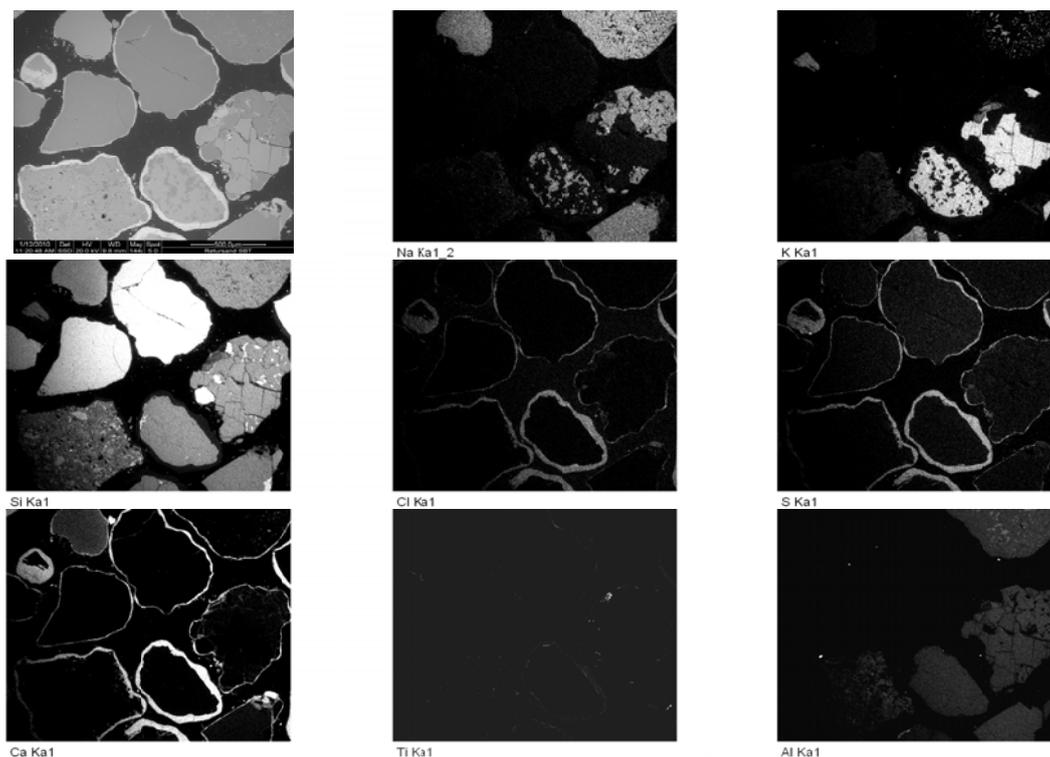
Figure 5: Return sand, RBT case, SEM photo (upper left) and EDX mapping on the cross section of the sample. Analyses of the elements Na, K, Si, Cl, S, Ca, Ti and Al.

The SEM-EDX analyses of the cyclone ashes showed no differences in structure or composition. In both cases Ca-Al-silicates, Ca-silicates, (K, Na)-Al-silicates, $CaSO_4$ and $CaCl_2$ were found. However, the filter ash showed some variations. The Cl concentration was 16% lower in the RBT case while the concentration of K and P was increased with 67% and 68% respectively, also some increase of Na, Mg, Si and Al was found in the elemental analysis. In addition the amount of As, Cd, Pb and Sb decreased with reduced bed temperature while Co, Ni, Cr, Cu and Zn increased. The results from the SEM-EDX were less clear but supported the elemental analysis.

3.3.3 XRD analysis on ashes

Table 5 shows the XRD results of the ashes, except the bed ash. It mainly contains glass, minerals and metals and ground to a fine powder the X-Ray powder Diffraction would not give relevant results. The presence of the chrystalline compounds found are denoted by M for much, L for less distinct identification and T for trace amount in Table 5.

In general, the XRD analysis gave less information than expected. The difference in concentration of chrystalline compounds in the two cases was very small. Return sand and return shaft ash contain much SiO_2 from the sand, diluting the samples to a degree making other chrystalls hard to detect. However, in the return sand sample from the RBT case $CaSiO_3$ was found in contrast to in the Ref case. The amount of detected $Ca_2Al_2SiO_7$ was also higher in RBT. Both these compounds are silicates with high melting temperatures, which are preferred as ash components in contrast to many silicates with

Table 5: Results from the XRD-analysis.

low melting temperature. No differences in the results from the return shaft ashes were found and the only difference seen in the cyclone ashes was that less $CaCO_3$ and more Al in metal form was found in the RBT case compared with the Ref case.

The XRD signal for filter ashes is generally weak because of the small particle size of filter ash (sub micron). However, there were a small reduction of the concentration of $Ca(OH)_2$, $CaSO_4$ and $Ca_3Al_2O_6$ found in the RBT case compared to the Ref case.

	Return sand		Return shaft		Cyclone ash		Filter ash	
	Ref	RBT	Ref	RBT	Ref	RBT	Ref	RBT
$Ca(OH)_2$							M	M^-
$CaClOH$							M	M
$CaCO_3$			T	T	L	L^-	L	L
CaO					T	T		
$CaSO_4$			L	L	L	L	L	L^-
$Na_4Ca(SO_4)_3$							T/L	T/L
$Ca_3Al_2O_6$			L	L	L	L	L	L^-
$Ca_2Al_2SiO_7$	L	M	M	M	M	M	L	T
$CaSiO_3$		L						
$NaCl$					L	L	M	M
KCl					T	T	M	M
SiO_2	M	M	M	M	M	M	T	T
$NaAlSi_3O_8$	M	M	M	M	L/M	L/M		
$KAlSi_3O_8$	M	M	M	M	L	L		
$Na_2Si_2O_5$					T	T		
Fe_2O_3	L	L	L	L	L	L	T	T
Al metal			L	L	L	L^+		
Fe metal			L	L	T	T		
MgO			L	L				
$Ca_5(PO_4)_3Cl$		$L^?$						

M= Much, L= Less, T= Trace

$^-$less than in Ref, $^+$more than in Ref, $^?$ Unserten result

3.4 Deposit formation

3.4.1 Element analysis and deposition rate

The deposit measurements were preformed two times during each combustion test and with the duration of two hours each. At each measurement two deposit probes carrying two deposit rings each were inserted in the measuring holes A and B respectively, as explained above in section 2.3. Photos of the deposit rings after the exposure are shown in Table 6. The mass gained by the rings during the two hours measurement is recalculated to deposit formation rate in Figure 6.

The deposition rate is clearly reduced in the RBT case compared to the Ref case. In position A the deposit rate increased with increased probe temperature as was expected, but in position B the rate decreased. No certain explanation for this was found. The difference in deposit formation rate was larger between the two measurement holes than between the combustion tests. This might be explained by the location of the holes just downstream the bend of the flue gas channel, see Figure 1a, in which the gas flow field is known to be very uneven across the duct. The variation of the local particle concentration is even larger, especially for the larger particles.

Table 6: Photos and gained weight of deposit rings after exposure at the super heaters in two different measurement holes (A and B in Figure 1b). Different material temperatures by row.

	Hole A		Hole B	
	Ref	**RBT**	**Ref**	**RBT**
435°C				
Gained weight (mg)	38.4	17.8	66.5	60.1
	Ref	**RBT**	**Ref**	**RBT**
500°C				
Gained weight (mg)	37.6	25.3	58.4	47.6
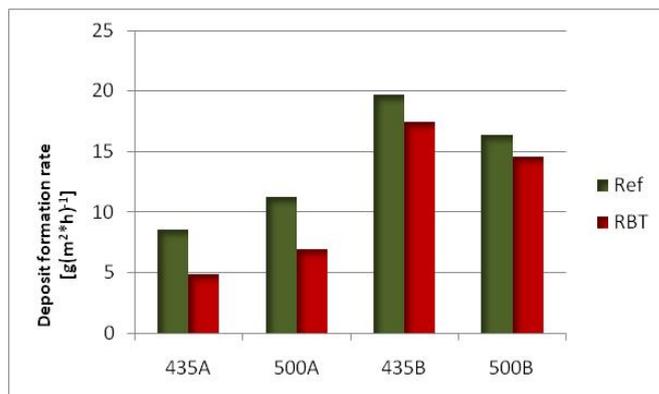
Figure 6: Measured deposit growths upstream of the super heaters. Ref case with green bars and RBT with red bars.

The element analysis of the deposits showed that the concentration of Cl was reduced and S increased on all rings in the RBT case compared with the Ref case, Figure 7. The difference in alkali distribution was not large, but a small increase of alkali in the RBT case was seen on all rings except for the deposit ring from the 500°C probes in position B. In the case of Ca the results were the opposite, Figure 7. The deposit composition varied more between the two measurement holes than between the combustion cases, as did the deposit formation.
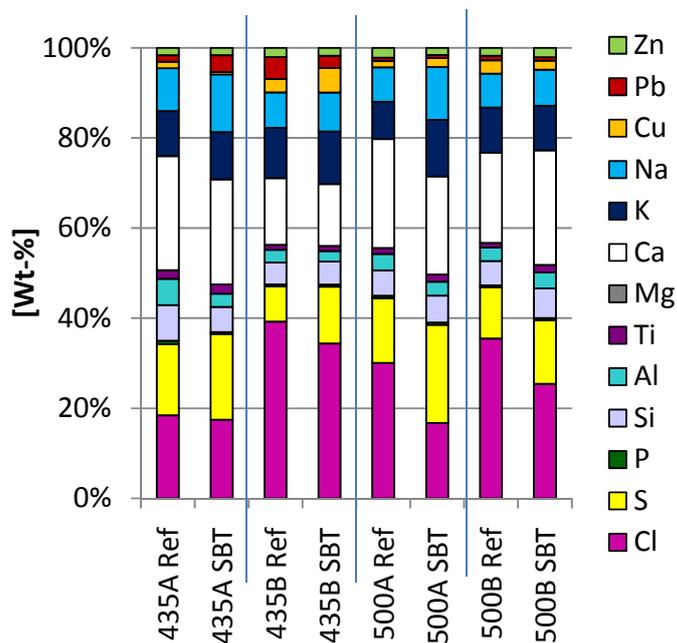
Figure 7: Elemental analysis of the deposit removed from the rings, oxygen excluded. The samples marked with temperature, measurement hole and combustion case.

3.4.2 **EDX analysis on deposits**

The EDX analysis on the wind side (0°) showed almost the same results as the deposit analyse, with a reduction of Cl and an increase of alkali and S in most cases, Figure 8. However, on the lee side (180°) the results varied among the rings. The deposits on the lee side were much thinner than on the wind side making the analyses less accurate. The fact that this analysis is made on the deposit surface and in small areas also contributes to that the results can vary more compared with the previous element analysis. However, this method shows the element distribution on the surface of the ring. In most samples no large changes in the element distribution were found, but on the wind side of the 500°C rings in position B in both combustion cases large alkali chloride crystals were covering the surfaces. At the surface of the 500°C rings in position A only tendencies to crystal formation were found. $CaSO_4$ were also found on all four rings.
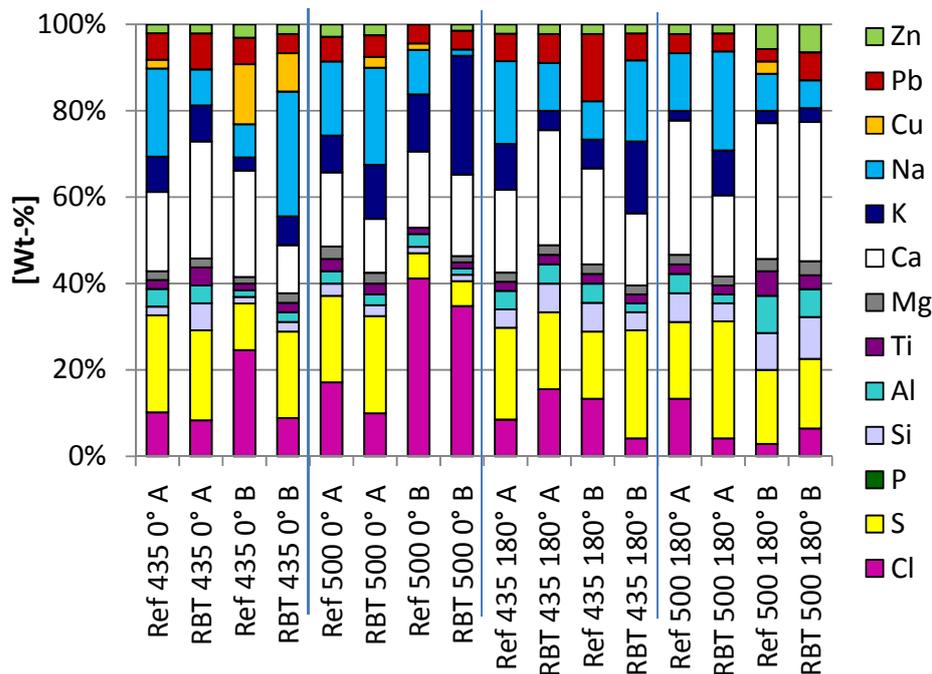
Figure 8: EDX analysis of the deposit rings, oxygen excluded. The samples marked with temperature, measurement hole and combustion case.

4. CONCLUSIONS

When the bed temperature was reduced from approximately 870°C to 720°C all agglomerates in bed ash and return sand disappeared. In addition, calcium-silicates were found in the deposits on the surface of the return sand particles and the concentrations of chlorine, sulphur and calcium-aluminium-silicates increased in the case with reduced bed temperature. Both alkali-aluminium-silicates and calcium-silicates have relatively high melting temperatures and stabilises the ashes. However, many of the compounds found in the deposits on the ash particles have melting temperatures lying between 750 to 850°C and thus cause agglomeration at the normal operation temperature of 870°C but not at the reduced bed temperature.

The fly ash flow was reduced with the lower bed temperature. In addition, the concentration of chlorine was reduced in the cyclone and filter ash.

The HCl concentration in the flue gas increased by the reduced bed temperature, which could depend on that less chlorine is bound as alkali chlorides. In addition, the deposit formation rate decreased by approximately 20% and the deposit contained less alkali and chlorine compared with the Ref case. In the deposits on the probes with the surface temperature of 500°C (corresponding to a steam temperature of 465°C) considerable amounts of KCl were found. Especially on the probes inserted in measure position B where the SEM-EDX analysis indicated the presence of KCl crystals. It was found to be larger differences in the deposit formation between the two measurement holes than between the two combustion cases. The probable reason for this big difference is the

sharp turn of the flue gas duct just in front of the measurement position causing uneven gas and particle flow fields.

5. REFERENCES

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6. Acknowledgements