Reduction of Emissions of Sulphur and Chlorine from Combustion of High Volatile Waste Fuels (Sludge) in Fluidised Bed

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Abstract: Co-combustion of sewage sludge with coal or wood as base fuels may cause high emissions of sulphur dioxide and hydrogen chlorine to the atmosphere. The conventional technique for sulphur capture in fluidised bed combustion using coal, lime addition, works well under co-combustion conditions with coal as base fuel but not with wood. The concentration of SO_2 certainly plays a role, but phosphorous, originating from the sewage sludge, forms calcium phosphate that may interfere with the sulphur capture reactions normally taking place when lime is added to the bed. Lime addition to the fluidized bed during combustion of pulp&paper sludge, not containing phosphorous and with similar sulphur levels as for the sewage sludge, gives a normal sulphur capture. Adding hydrated lime to a bag filter is an alternative to lime addition to the bed that can be used when fuels with high content of phosphorous are co-combusted with wood. Hydrated lime also captures chlorine in the bag filter

Keywords: Co-combustion, sewage sludge, sulphur capture, chlorine capture, phosphorous interference

1. INTRODUCTION

Combustion of sewage sludge has been practiced for decades in many types of combustors [1]. However, co-combustion of sludge with another fuel (the base fuel for which the plant was designed) has been suggested only recently. The idea is to burn sewage sludge in conventional solid fuel boilers like fluidised bed boilers, normally used for power and/or heat production. Within the European Union the regulation of emissions from mono-combustion of wastes like sludge has been adapted to include co-combustion in conventional boilers, making the procedure for acceptance and approval easier [2]. Emissions of sulphur and chlorine are treated in the present work with respect to the EU incineration directive. Sewage sludge contains fairly high concentrations of sulphur, and emissions of sulphur dioxide (SO_2) may be a problem if the sulphur is not captured. The conventional technology for fluidised beds (lime addition to the bed) is studied with coal or wood as base fuels and various types of sludges having high sulphur concentrations. An alternative sulphur capture technology (lime addition to the bag filter) is applied for comparison. The chlorine emission problem is covered as well. The emission level stated for chlorine in the EU incineration directive is low. An active method like lime addition to the bag filter is demonstrated as one alternative allowing to treat the problem in a simple way.

2. EXPERIMENTAL BACKGROUND

2.1 The boiler

The 12 MW_{th} circulating fluidized bed (CFB) boiler, located at Chalmers University of Technology was used for the tests. The boiler is built for research but has all the features of a commercial unit. A presentation of the boiler is found in Ref. 3.

2.2 The fuels

The base fuels were coal or pellets. The coal originated from the Katowice district in Poland. The wood pellets were produced by "AB Svensk Brikettenergi" from sawdust obtained as a waste from domestic trees like pine and birch. Bark pellets were produced from excess amounts of bark at a pulp&paper plant, site B. The additional fuels were two different municipal sewage sludges and two sludges from the pulp&paper industry. One of the municipal sewage sludges was produced as mechanically dewatered sludge from "Ryaverket". This plant is the second largest wastewater

treatment plant in Sweden, taking care of wastewater from 580000 inhabitants of the city of Göteborg and surroundings. The second sludge involved was dewatered sludge from the wastewater treatment plant in Alingsås. This plant treats wastewater from 35000 inhabitants. Both municipal wastewater treatment plants produce digested sludge but employ different precipitation chemicals for phosphorous removal. "Ryaverket" employs ferrous iron supplied as iron sulphate ($FeSO_4$) and the plant in Alingsås aluminium sulphate ($Al_2(SO_4)_3$). Apart from sewage sludge, two sludges produced in the water treatment process of two pulp&paper sites (site A and B) were included in the test programme. From site A a chemically precipitated sludge was produced and from site B the sludge was a mix of fibre sludge and sludge from a biological cleaning step. The content of moisture, combustibles and ash were analysed by a MAC 400 Proximate Analyzer 785-700 system. The main components were analysed by ICP-MS (inductive coupled plasma with a mass spectrometer as detector) at an accredited laboratory. The properties of the fuels are given in Table 1.

2.3 Experimental procedure

The test program consisted of 35 individual tests divided into eleven test series A to K according to Table 2. The operating conditions were chosen to represent a typical case of a CFB boiler with a bottom bed temperature of 850 °C, an excess air ratio of 1.2, splitting of air supply into primary and secondary air, inlet of secondary air at 2.2 meter and a load corresponding to a fluidising velocity of 5 m/s at the top of the combustion chamber. The arrangements of the research boiler allow keeping some of the parameters constant and similar in all tests. Other parameters are then stabilized on certain values (e.g temperature in top of furnace) due to the heat balance. The average and standard deviation for these parameters in the 35 tests are given in Table 3. The parameters that were actively changed in the test program (amount of sludge, type of sludge, type of base fuel, lime addition) are not included in Table 3. As can be seen in Table 3, the operating conditions could be kept quite stable, despite the great differences between the tests. The only parameter that changed was the temperature in the top of the combustion chamber and to some extent also the temperature in the exit duct from the hot cyclone. The reason for the stable operation is that the research boiler is equipped with a control system that maintains the airflow constant when the load is set. The fuel flow is then controlled in relation to the oxygen concentration in the stack, and pressure fluctuations on the waterside of the boiler are balanced by a heat exchanger. This control system

Table 1. Fuel analysis

	Sewage sludge[1]	Sewage sludge[2]	Sewage sludge[3]	P&P sludge[4]	P&P sludge[6]	Wood pellets	Bark pellets	Coal [7]
Precipitation agent	$FeSO_4$	$Al_2(SO_4)_3$	$FeSO_4$	PAC[5]	not known	NR	NR	NR
Proximate analysis								
Water (wt-%, raw)	72.0	77.8	71.8	71.2	78.6	8.0	10.3	9.0
Ash (wt-%, dry)	46.0	42.6	46.1	11.8	15.0	0.4	3.0	17.5
Combustibles (wt-%, dry)	54.0	57.4	53.9	88.2	85.0	99.6	97.0	82.5
Volatiles (wt-%, daf)	94.4	85.3	88.3	77.4	83.1	81.7	77.6	32.7
Ultimate analysis (wt-%, daf)								
C	52.6	50.2	51.0	49.2	88.9	50.3	53.6	84.9
H	7.2	7.3	7.4	6.5	12.0	6.1	6.2	5.0
O	33.3	36.2	34.1	42.1	77.6	43.5	39.7	7.7
S	1.4	1.2	1.6	1.7	2.7	0.01	0.04	0.73
N	5.4	5.0	5.7	0.46	5.0	0.09	0.46	1.57
Cl	0.1	0.1	0.1	0.03	0.03	0.01	0.02	0.08
Lower heating value (MJ/kg)								
Hu, daf	20.50	19.50	19.49	18.51	17.86	18.80	20.32	33.35
Hu, raw	2.78	2.24	1.17	2.93	1.29	17.20	17.43	24.65
Ash analysis (g/kg dry ash)								
K	13.3	10.7	15.1	2.5	11.6	82	50.2	11
Na	7.3	6.9	8.5	10.9	13.7	6.7	4.8	1.9
Al	73.3	193	82.4	271	108	12.2	13.1	84
Si	127	115	142	84.9	112	79.7	72.4	290
Fe	160	42.1	152	16.1	16.8	20.9	6.8	47
Ca	40	38.0	48.4	1.2	180	164	263	30
Mg	9.9	5.3	11.9	40.0	19.7	26.4	20.1	18
P	58.6	61.3	67.9	1.3	4.5	12.7	11.9	1.0
Ti	4.4	9.6	4.7	36.4	3.6	0.7	1.0	0.69

(1) = used in test series A, C and E; (2) = used in test series B, D and E

(3) = used in test series G; (4) = chemical precipitated sludge from the pulp&paper industry, site A; (5) = precipitation agent is polyaluminium chloride,

(6) = sludge from the pulp&paper industry, site B, mix of fibre sludge and sludge from an biological cleaning step

(7) = bituminous coal also used in "Coal series2" in ref. 4

daf= dry and ash free, raw=as received, NR=not relevant

maintains a very stable condition that is important when sulphur and chlorine capture by lime are to be studied. All tests except five were run between 9-12 h. Evaluation of gas concentrations and operating parameters were performed after stable conditions were achieved.

2.4 Measurements of emissions

Emissions were recorded in the flue gas duct ahead of the flue gas fan by three gas extraction analysing systems, as described in Ref. [3]. Two of the systems analyse the flue gases on dry gas using individual analysers for each component. In the third system a FTIR (Fourier transform infrared) instrument measures on hot (200 °C) gases without removal of moisture in the gas. Hence, SO_2 is measured by three gas analysis systems and HCl is recorded by the FTIR.

3. Results

The results are presented in seven steps in Sections 3.1 to 3.7. First, the sulphur capture performance for co-combustion of sewage sludge with coal will be compared with the

Table 2. The test series

Series	Type of sludge	Base fuel	Precipitation agent	Lime addition
A	sewage sludge	wood pellets	$FeSO_4$	none
B	sewage sludge	wood pellets	$Al_2(SO_4)_3$	none
C	sewage sludge	wood pellets	$FeSO_4$	to the bed
D	sewage sludge	wood pellets	$Al_2(SO_4)_3$	to the bed
E	sewage sludge	wood pellets	$FeSO_4$	to the bag filter
F	sewage sludge	wood pellets	$Al_2(SO_4)_3$	to the bag filter
G	sewage sludge	wood pellets	$FeSO_4$	to the bed or bag filter[1]
H	P&P sludge[2]	wood pellets	PAC[3]	to the bed or bag filter
I	P&P sludge[4]	bark pellets[5]	not known	-
J	sewage sludge	coal	$FeSO_4$	to the bed
K	sewage sludge	wood pellets	$FeSO_4$	to the bed

(1) = Higher lime flows than in test series C and E.

(2) = Chemical percipitated sludge from the pulp&paper industry, site A.

(3) = Precipitation agent is polyaluminium chloride, PAC

(4) = Sludge from the pulp&paper industry, site B. Mix if fibre sludge and sludge from a biological cleaning step.

(5) = Test of bark pellets as base fuel. Test series includes reference cases with only bark pellets,

bark pellets+sludge, barkpellets+sludge+lime to bed and finally bark pellets+sludge+lime to bag filter.

Table 3. Average and standard deviation of the operating parameters not changed in the test program (35 tests).

	average	s-dev.
load, MW_{th}	6.2	0.3
bed temp., °C (bottom)	849	2.1
bed temp., °C (top)	862	23.7
exit temp. of after burning chamber, °C	843	15.8
temp. after economiser, °C	153	5.2
temp. after bag filter, °C	148	3.3
excess air ratio	1.23	0.02
primary air flow/ total air flow,%	55	4.4
total riser pressure drop, kPa	6.4	0.2
superficial flue gas velocity at top of riser U_{top}, m/s	5.1	0.3

s-dev.=standard deviation

corresponding tests with wood pellets as base fuel. Second, the sulphur capture in the tests series A-F will be shown. Third, sulphur capture with a higher lime flow is discussed. Fourth, sulphur capture using pulp&paper sludge instead of sewage sludge is illustrated. Fifth, sulphur capture with hydrated lime to the bag filter is compared to lime addition to the bed. Sixth, sulphur capture by calcium in the fuel ash is presented and finally, the chlorine capture is discussed.

3.1 Sulphur capture with coal and sewage sludge

Figure 1 shows SO_2 emissions from co-combustion of sewage sludge with either coal or wood pellets. For each base fuel the maximum theoretical emission is given as a solid line corresponding to a situation when all sulphur in the fuel feed is assumed to be oxidised to SO_2 and no capture of sulphur takes place in the system. The difference between the solid lines and the dotted lines (the actual measured SO_2 concentrations) is the sulphur capture. The large difference between the two curves for coal corresponds to a sulphur capture of more than 90%. With wood pellets as base fuel the curves are closer to each other, giving a sulphur capture of less than 50%. More sulphur added with the fuel leads to higher SO_2 concentrations in the furnace and faster reactions with the lime added to the bed. This favours the coal case, and further tests (test series A-F) were performed to study the combination of wood pellets (having a low sulphur content) as base fuel and sewage sludge as additional fuel.
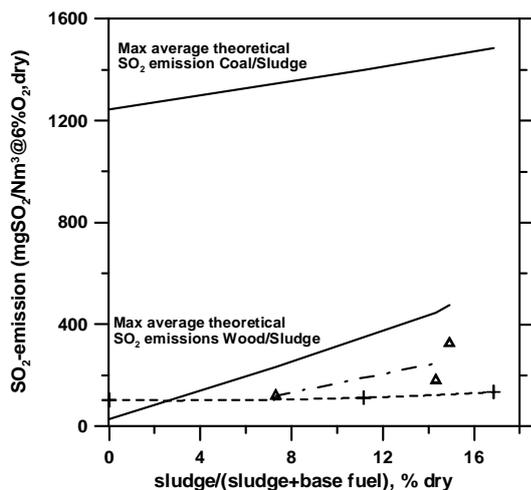
Figure 1. Emissions of sulphur for test series J and K. Base fuel: coal or wood pellets; additional fuel: sewage sludge with FeSO$_4$ as precipitation agent
+ + + lime to bed, coal
△ △ △ lime to bed, wood

3.2 Sulphur capture with wood pellets and sewage sludge

Test series A-F represent the main part of the test program with two sludges, two feeding ratios, and with three alternatives for sulphur capture: no lime addition, lime to the bed and hydrated lime added ahead of the bag filter. The results are plotted in Figures 2 and 3 in a similar way as in Figure 1 with a solid line for the theoretical SO_2 emissions and dotted lines for the different lime conditions. From Figure 2 is it obvious that the case "no lime addition" and "lime to bed" ends up with similar SO_2 emissions, which are almost equal to the level of the theoretical SO_2 emission. This means that no sulphur retention is achieved at all. The only case with some sulphur capture was the one with hydrated lime addition ahead of the bag filter. Figure 2 represents the case when the phosphorous was precipitated by FeSO$_4$ at the wastewater

plant. The iron phosphate then produced ends up in the sludge. It is analysed as individual species and given as part of the ash analysis in Table 1. The high levels of iron and phosphorous are clearly seen compared to the analysis of the pulp&paper sludges and the base fuels. Changing the precipitation agent to $Al_2(SO_4)_3$ clearly changes the analysis of the ash components Fe and Al in Table 1. The P content is about the same and distinctly higher than for the pulp&paper sludges. Results from the combustion tests with the sludge produced from wastewater precipitated by $Al_2(SO_4)_3$ are found in Figure 3. Both similarities and differences from Figure 2 are seen. The solid curve for the theoretical SO_2 emissions is higher than the two dotted lines for "no lime" and "lime to bed" indicating some desulphurisation. However the solid line representing the sludge addition tests is based on the average value of a sulphur content of 1.25% (Table1) calculated from individual analyses of 3 sludge samples. Using a standard deviation of 0.08 there is a range around the solid line representing the theoretical SO_2 emission as function of sludge supply in Figure 3 (as well as in Figure 2),. Despite the uncertainty of the theoretical SO_2 emission levels the small difference between the cases with "no lime" and "lime to bed" (as in Figure 2) is obvious. This means that the capture of sulphur by the lime in the bed does not perform well. Two explanations for this observation are presented:
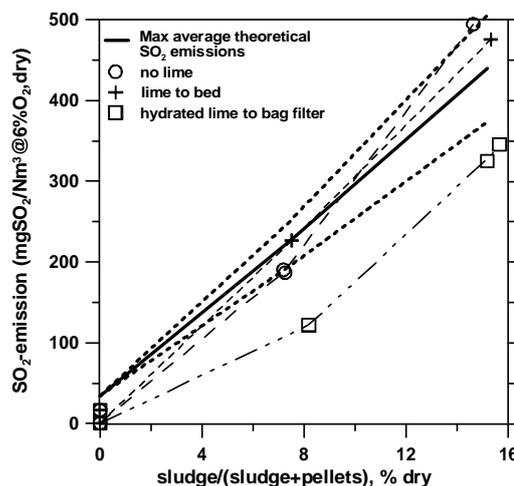
Figure 2. Emissions of sulphur for test series A, C and E. Base fuel: wood pellets; additional fuel: sewage sludge with FeSO$_4$ as precipitation agent. Thick dotted lines around the "Max average theoretical SO_2 emissions" represent the analytical uncertainty of the S-content in the sludge.

Explanation 1: If lime is mainly located in the bottom of the combustion chamber and the SO_2 from the high volatile fuels is formed higher up in the furnace, SO_2 and lime never have the opportunity to react with each other.
Explanation 2: A parallel reaction leads to deactivation of the lime (CaO) otherwise available for reaction with SO_2. The reaction of phosphorous originating from the sludge, forming calcium phosphate ($Ca_3(PO_4)_2$) is suggested to be the reaction interfering with the sulpfation reaction:

$$CaO(s) + \tfrac{1}{2}O_2\,(g) + SO_2\,(g) \longrightarrow CaSO_4\,(s) \qquad (1)$$
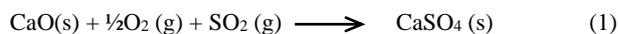
The formation of calcium phosphate could be interfered by the precipitation agent used in Figure 3. The formation of aluminium phosphate could partly deactivate the phosphor leading to some desulphurisation as shown in Figure 3.
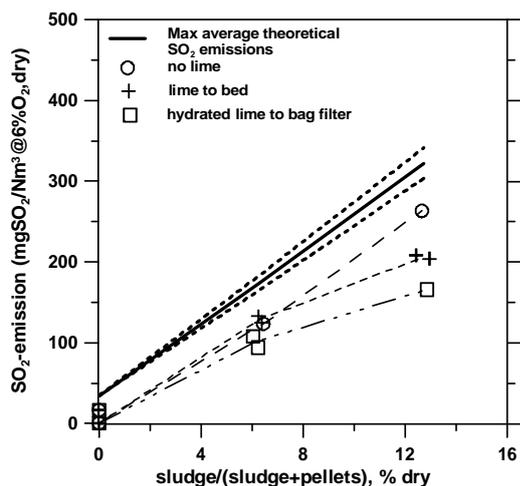
Figure 3. Emissions of sulphur for test series B, D and F. Base fuel: wood pellets; additional fuel: sewage sludge with $Al_2(SO_4)_3$ as precipitation agent. Thick dotted lines around the "Max average theoretical SO_2 emissions" represent the analytical uncertainty of the S-content in the sludge.

The first explanation should also lead to poor desulphurisation for the high volatile containing pulp&paper sludges. This is the reason way test series H and I was performed, Section 3.4.
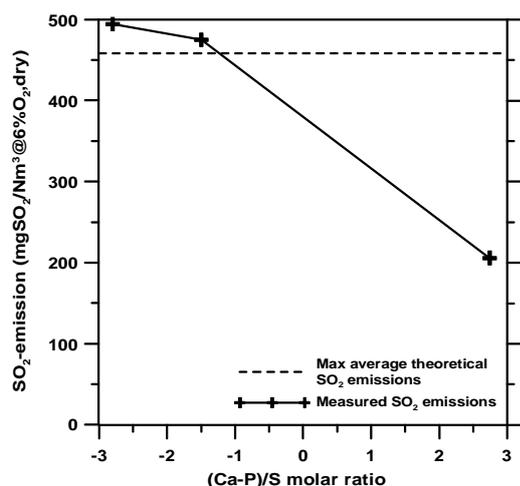
Figure 4. SO_2 emissions as function of (Ca-P)/S molar ratio. Base fuel: wood pellets; additional fuel: sewage sludge with $FeSO_4$ as precipitation agent. Combination of tests from test series A, C and G with either no lime supply or lime added to the bed.

3.3 Sulphur capture with wood pellets and sewage sludge, higher lime flow

In order to test explanation 2 (interference of phosphorous), test series G (high lime flow) was carried out and the results were combined with those from test series A and C. A recalculation of the molar ratio of Ca/S as (Ca-P)/S is done in order to clearly show how much of the Ca that could be occupied to form calcium phosphate according to the stoichiometric formula $Ca_3(PO_4)_2$. This way of expressing the amount of Ca available for sulphur capture, Figure 4, clearly shows that only in test G there is an excess of lime even if the phosphorous in the sludge forms calcium phosphate. A clear reduction of the SO_2 emission is measured in this test. In the cases with coal sulphur capture appears to be satisfactory. The

reason is that (Ca-P)/S was in the order of 3, because the lime supply was adjusted to the sulphur content of the coal, and the impact of phosphorous is present but not clearly visible.

3.4 Sulphur capture with wood pellets and pulp&paper sludge

The three tests in Figure 4 are replotted in Figure 5 for comparison with similar tests involving pulp&paper sludge. Figure 5 contains a great deal of information. The bars represent theoretical and measured SO_2 emissions. Apart from that, the ratio (Ca-P)/S is given, based on the amount of Ca added and as total Ca, including the Ca in the fuel ash. A substantial amount of Ca is present in the fuel ash of sewage sludge. Pulp&paper sludge A contains only minor amounts of phosphorous and calcium but more sulphur than sewage sludge. Maintaining constant the added amount of Ca from the third test with sewage sludge led to a large increase of the calculated ratio of (Ca-P)/S in the test with pulp&paper sludge A. The measured SO_2 emission in this test is about the same as for the test with sewage sludge and high lime flow. This means that the desulphurisation and lime efficiency with pulp&paper sludge A is better because there is no phosphorous that can interfere. One can argue that the higher sulphur concentration in this test promotes faster reaction of SO_2 with the lime and thereby better desulphurisation, and this argument is in principle correct. The test with pulp&paper sludge B leads to the same levels of SO_2 as the test with sewage sludge. Despite a lower flow of added lime for the test with pulp&paper sludge B, the high Ca content of this sludge in combination with bark pellets as base fuel (that also add to the Ca flow from fuel ash) leads to the highest ratio (Ca-P)/S of all tests, 7.2. Very low emission of SO_2 is therefore achieved. Desulphurisation and lime efficiency is better for the pulp&paper sludge B than for sewage sludge. This means that there are two independent tests with two different pulp&paper sludges not containing phosphorous that give better desulphurisation than the sewage sludge. All sludges are high volatile fuels, but only the sewage sludges containing phosphorous lead to poor desulphurisation when adding lime to the bed. Explanation 2, that phosphorous interferes, is a more likely reason, and explanation 1 (the volatile content) is less dominant.
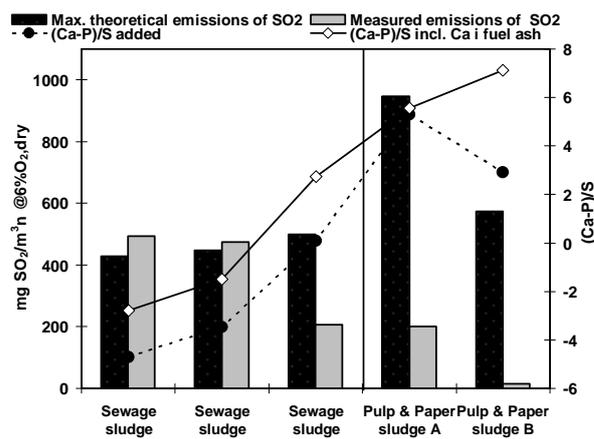
Figure 5. Emissions of sulphur dioxide for the tests with sewage sludge with either no lime supply or lime to bed (test series A, C or G compared with pulp&paper sludge tests from test series H or I with lime addition to the bed.

3.5 Comparison of lime addition methods for sulphur capture

Figure 6 compares hydrated lime addition ahead of the bag filter with lime addition to the bed for three sludges: one sewage sludge and two pulp&paper sludges. In general, hydrated lime addition to the bag filter is less effective than lime addition to the bed. This is obvious when comparing one sludge type at the time. The reason is probably a competition for the hydrated lime by chlorine capture in the bag filter. This will be further discussed in Section 3.7. The fuel ash of sewage sludge and pulp&paper sludge B contains a large amount of calcium, seen as a large difference between the "(Ca-P)/S added" and "(Ca-P)/S incl. Ca in fuel ash" in Figure 5. In the two cases with active addition of hydrated lime this extra calcium is added to the bed anyway. The two sludges, sewage sludge and pulp&paper sludge B, can be directly compared, because the maximum theoretical levels of the SO_2 emissions are about the same as seen in Figure 6. Sewage sludge always gives less desulphurisation regardless of whether lime is added in the bed or as hydrated lime ahead of the bag filter. The difference in sulphur capture adding lime to the bed was explained above as caused by interference of phosphorous. A large fraction of the total amount of lime in tests with sewage sludge and pulp&paper sludge B was supplied to the bed with the fuel ash, and phosphorous can interfere with the sulphur capture reaction in the tests with sewage sludge. In the test with pulp&paper sludge B, where no phosphorous is present, the calcium could either react with sulphur in the combustion chamber or the calcium is entrained unreacted to the bag filter and adds to the hydrated lime.

3.6 Sulphur capture by calcium in fuel ash

The three tests in the tests program with no co-combustion of sludge and no lime added to the boiler are reference cases. The SO_2 emissions in these three tests are seen in Figure 7. Reference case 1 and 2 were performed with wood pellets and reference case 3 with bark pellets. Table 1 shows that the calcium content in the ash from bark pellets is 60 % higher than in ash from the wood pellets. Bark pellets contain more ash and, despite somewhat higher sulphur content, the (Ca-P)/S value becomes 16.3. Also wood chips combustion leads to high ratios of (Ca-P)/S, and in all three reference cases the measured emissions of SO_2 were low. Adding pulp&paper sludge B (with an ash that also contains calcium) to the bark pellets (the fourth test case in Figure 7) led to a decrease of the (Ca-P)/S value to 4 but still an impressive desulphurisation of almost 80 % was maintained. Since the emission limit is 200 mg SO_2/m_n^3 (EU incineration directive for waste combustion [2]), the combination of a base fuel and a pulp&paper sludge with high calcium content in the ash does not need any additional lime supply. This requires combustion in a fluidised bed boiler. Other combustion systems like flame combustion or combustion in grate furnaces equipped with electrostatic precipitators will probably not give the same good desulphurisation as shown for the pulp&paper sludge B in Figure 7.

3.7 Chlorine capture

Chlorine capture reactions can take place in a flue gas duct or in a bag filter by the following reactions [5]:

Between 300-400 °C calcium oxide reacts with HCl according to:
$$CaO(s) + 2\ HCl(g) \longrightarrow CaCl_2\ (s) + 2H_2O(g) \quad (2)$$

Between 170-230 °C:
$$Ca(OH)_2(s) + HCl(g) \longrightarrow H_2O(g) + Ca(OH)Cl(s) \quad (3)$$
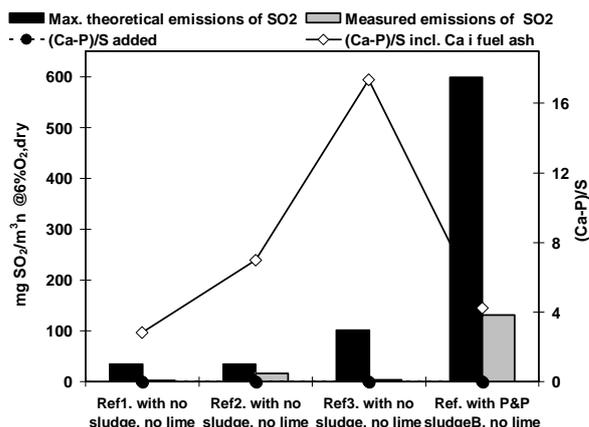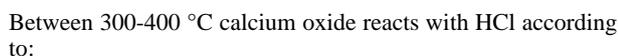
Figure 7. Emissions of sulphur dioxide in the three reference cases with no sludge and no lime supply. Fourth test from series I with pulp&paper sludge B and no lime supply.

In a bag filter the following reactions take place [6]:

At 120 °C chlorine is captured by hydrated lime:
$$Ca(OH)_2(s) + 2\ HCl(g) \longrightarrow CaCl_2*2H_2O(s) \quad (4)$$
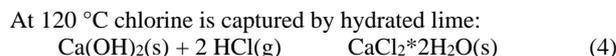
Hydrated lime can also react with sulphur dioxide producing calcium sulphite:
$$Ca(OH)_2(s) + SO_2(g) \longrightarrow CaSO_3*\tfrac{1}{2}H_2O(s)+\tfrac{1}{2}H_2O(s) \quad (5)$$
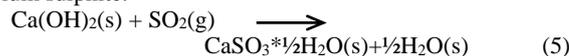
The calcium sulphite can react with hydrogen chlorine and SO_2 is then released again according to:
$$CaSO_3*\tfrac{1}{2}H_2O(s) + 2\ HCl(g) + \tfrac{1}{2}H_2O(g) \longleftrightarrow CaCl_2*2H_2O(s)+ SO_2(g) \quad (6)$$
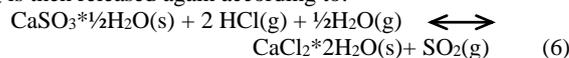
Finally, the calcium sulphite can be oxidized to calcium sulphate according to:
$$CaSO_3*\tfrac{1}{2}H_2O(s) + \tfrac{1}{2}\ O_2(g) + {}^{3/2}\ H_2O(g) \longrightarrow CaSO_4*2H_2O(s) \quad (7)$$
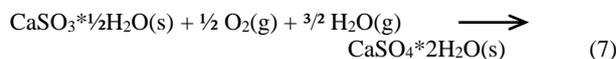
The reactions can be useful in the interpretation of the results on chlorine capture. In Figure 8 the HCl emission is reported for five tests with lime addition to the bed. In none of the three tests with sewage sludge as additional fuel chlorine was captured (the difference between the bars for each test in the three cases reflects the accuracy of the chlorine analyses). This
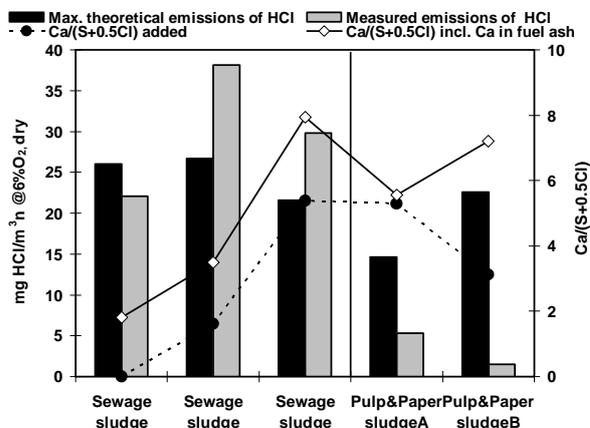
Figure 8. Emissions of hydrogen chlorine for the tests with sewage sludge compared with pulp&paper sludge A and B. Lime addition to the bed
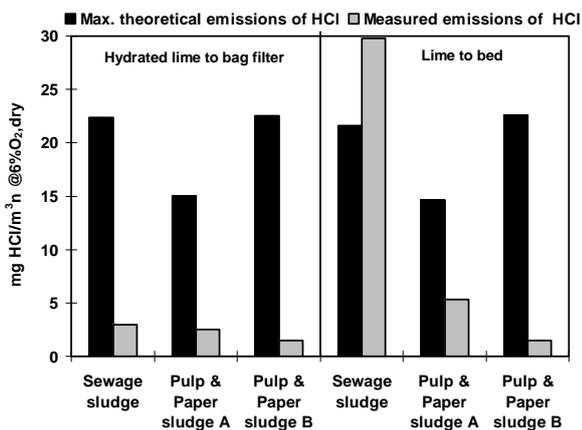
Figure 9. Comparison of lime addition methods for chlorine capture. Left part of figure: hydrated lime ahead of bag filter, test series G H and I. Right part of figure: lime addition to the bed, tests series G, H and I.

result is quite different from the two cases with pulp&paper sludge, where some chlorine retention was observed, Figure 8. Lime added to the bed is entrained to the flue gas duct and bag filter where it takes part in chlorine capture reactions according to Reactions 2, 3 and 4. Capture of chlorine directly by CaO in the bed is not likely [7], [8] at the high temperatures prevailing, and the capture efficiency is low. Chlorine capture by entrained lime particles at the lower temperatures of the gas duct and the filter is therefore more likely to be the relevant process. In the three cases with sewage sludge, the poor sulphur capture performance was explained as interference from phosphorous forming calcium phosphate. Such formation of calcium phosphate also blocks the reaction of entrained lime particles with chlorine in the flue gas duct and bag filter. For the two pulp&paper sludges not containing phosphorous some chlorine capture was measured. This may explain the especially good chlorine capture performance for the pulp&paper sludge B when a major part of the total amount of calcium was added as fine ash particles elutriated to the flue gas duct and bag filter. If such a favourable situation cannot be achieved, then hydrated lime added directly ahead of the bag filter is an effective method for chlorine capture. This is illustrated in Figure 9 where the effect of lime addition on chlorine capture is directly compared for three different sludges. Addition of hydrated lime upstream of the bag filter always leads to a reduction of chlorine. Chlorine is reduced first. When the chlorine level is low, also the sulphur concentration begins to fall. This is shown in a special response test carried out upon starting the flow of hydrated lime, explained by Reaction 6, where calcium sulphite reacts with chlorine releasing sulphur. In this case chlorine and sulphur capture interacts with each other leading to low sulphur capture, (Figure 6, left part of the figure compared to the right part). Hydrated lime is more effective in reducing chlorine than lime addition to the bed, even if phosphorous is not present, (compare pulp&paper sludge A in Figure 9). If phosphorous is present in the sludge, addition of hydrated lime to the flue gas is the only way to prevent emissions of both chlorine and sulphur. If a large part of the calcium is added to the bed in the form of small fuel ash particles, such as in the case with pulp&paper sludge B, the chlorine capture efficiency is the same as if the lime is added in the form of hydrated lime ahead of the bag filter. In this case no system for addition of hydrated lime is needed.

4. CONCLUSIONS

The following conclusions can be made:

- There is a poor sulphur capture performance for co-combustion of sewage sludge with wood in comparison to sulphur capture during co-combustion with coal.

- There is a poor sulphur capture performance for co-combustion of sewage sludge with wood regardless of precipitation agent used for phosphorous recovery at the wastewater treatment plant.

- Recalculation of the molar ratio of Ca/S into (Ca-P)/S reveals that normal lime flows to the boiler do not give any excess of lime available for sulphur capture if $Ca_3(PO_4)_2$ is formed.

- Co-combustion of wood with pulp&paper sludge that does not contain any phosphorous that can interfere with the sulphur capture reaction shows a proper desulphurisation performance.

- Combination of bark as base fuel and pulp&paper sludge with high Ca contents in the ash can lead to high desulphurisation in fluidised beds.

- Chlorine can be captured by adding hydrated lime to the flue gas duct ahead of a bag filter.

- Lime elutriated from the bed can take part in chlorine capture reactions in the flue gas duct or bag filter if phosphorous is not present in the sludge.

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