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CO-COMBUSTION OF PULP- AND PAPER SLUDGE WITH WOOD – EMISSIONS OF NITROGEN, SULPHUR AND CHLORINE COMPOUNDS

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ABSTRACT

Sludge from wastewater treatment plants in five Swedish pulp and paper mills has been burned together with wood in a circulating fluidised bed (CFB) boiler. The sludge was either mechanically dewatered or pre-dried. The mechanically dewatered sludge had to be fed with a pump, but the pre-dried sludge could be fed by the fuel feed system normally used for coal, wood chips or wood pellets. In parallel to the combustion tests in the CFB boiler the sludges were also investigated as single fuels in a small laboratory FB.

The Swedish pulp and paper industry produces three major fractions of sludge: pure fibre sludge, sludge produced by employing a precipitation species like ironaluminiumsulphate, and finally, sludge subjected to biological cleaning. The way of production of the sludge influences its content of, for example, nitrogen, sulphur and chlorine, but the composition of the sludge is also influenced by the pulp and paper process. The present measurements show that the concentrations of nitrogen, sulphur and chlorine in the sludge have a great impact on the corresponding gaseous emissions from combustion. Actions to prevent these emissions could be necessary, depending on the origin of the sludge and treatment process used. In the present project all sludges were burned with wood-pellets as the main fuel under identical operating conditions, typical for a CFB boiler. Wood pellets were chosen as a well defined, low-polluting fuel that makes comparison of emissions from the sludges clear. Co-combustion with wood-pellets has the advantage of enabling operation also with wet sludges that cannot be used as single fuels without pre-drying. No actions were taken to improve sulphur and chlorine retention, by for example adding limestone. From a combustion point of view the co-combustion works well with low levels of carbon monoxide present in the flue gas and no light hydrocarbons.

INTRODUCTION

The use of land filling as a means of deposition of pulp&paper mill sludge is becoming more difficult because of increasing environmental demands on disposal sites. Lack of suitable locations for disposal sites and increasing costs for preparation makes land filling an expensive alternative in the future. Thermal treatment could be a better solution to the problem. With a proper technology the energy content can be recovered, and in the case of co-combustion with coal an effective reduction of the CO_2 emission is achieved. Combustion of pulp&paper mill sludge in fluidised bed boilers has been demonstrated in a number of publications [1-7]. The sludge was either burned as a single fuel [1], together with coal [3-6], or biomass [2] or other refuse derived fuels [7]. Unlike the situation described in these papers, where only one type of sludge was studied at the time, here results are presented from different kinds of pulp&paper mill sludges. The selection of sludges aimed at achieving a difference in, for example, the content of nitrogen, sulphur and chlorine and to study the corresponding emissions.

EXPERIMENTAL BACKGROUND

The Boiler

The 12 MW$_{th}$ circulating fluidized bed (CFB) boiler, located at Chalmers University of Technology was used for the tests, Figure 1. The boiler is built for research but has all the features of a commercial unit. The combustion chamber (1) has a square cross-section of about 2.25 m^2 and a height of 13.6 m. Fuel is fed to the bottom of the combustion chamber through a fuel chute (7). The circulating solids are separated in the primary cyclone (2) and transported through the particle return leg (3), the loop seal (4), and, during combustion of pure wood pellets, also through the external heat exchanger (5), back into the combustion chamber. Primary combustion air is supplied to the wind box (6) below the gas distributor, and secondary air was supplied in (9). The other secondary air ports (10-12) were not used. After passing the exit duct of the cyclone (13), the flue gases are cooled to 150 °C in the convection path and fly ash is separated from the flue gases, first in a secondary cyclone and then in a bag filter.

The Laboratory Test Unit

The laboratory unit, Figure 2, consists of a quartz glass reactor (inner diameter=0.07 m, length=1.5 m), surrounded by an electrically heated oven that can be controlled up to 1100 °C. The wet sludge was dried and briquetted into pieces of 2 g each. The briquettes were fed into the reactor one by one through a carousel feeder (6 g/min). The bed temperature was measured with an unshielded thermocouple and was kept constant at 850 °C. The relation between primary and secondary air was 3:1.The flue gas was sampled in the top of the reactor with a heated probe. After filtration the sample gas was distributed to the gas analysers.

The Fuels

The wood pellets were produced from saw dust (pine) by "AB Svensk Brikettenergi". The sludges originated from wastewater treatment plants of five Swedish pulp and paper mills. The sludge consists mainly of three fractions: pure fibre sludge, sludge produced by chemical precipitation or by a biological cleaning step. Depending on the arrangement in the mills, each of the six different sludges in the test program was either a mixture of fibre sludge and chemically precipitated sludge, or pure fibre sludge or pure biological sludge. From Table 1 the origin of sludges is declared together with their properties related to combustion. One of the sludges was pre-dried, while the other five were mechanically dewatered to various moisture contents, as can be seen in Table 1. In order to feed the wet sludge cake into the boiler a sludge pump (a development of a piston pump normally used for cement) was installed in the research facility.

Experimental Procedure

The operating conditions of the tests are given in Table 2 (pre-dried sludge) and Table 3 (wet sludges). The arrangements of the research boiler allows to keep the operating conditions similar in all tests, only changing the amount of sludge added and type of sludge. It is possible to feed higher fractions of pre-dried sludge than mechanically dewatered sludge, as reflected in the test series with Sludge 1 (Table 2) compared to the wet sludges of Table 3. 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. No lime was added to the combustion chamber, and the emissions of sulphur dioxide (SO_2) and hydrogen chloride (HCl) reach values that reflect the concentrations of sulphur and chlorine in the fuel.

Measurements of Emissions

Emissions were recorded in the flue gas duct ahead of the flue gas fan by three independent gas-analysing systems. The first system, A (Figure 3) consists of at set of analysers that measure the emissions of SO_2, nitric oxide (NO), nitrous oxide (N_2O) and carbon monoxide (CO) on dry flue gases. The second set of analysers, B (Figure 4) is similar to the first one. These analysers are normally used for analysing gases sampled from the furnace, but they can be operated in parallel with the A-system as a backup and check. In the B system a total hydrocarbon analyser, equipped with a flame ionisation detector (FID), is included. The third system consists of an on-line Fourier Transform Infra-Red (FTIR) analyser, Figure 5. This instrument is developed for flue gases from a waste incinerator and hot combustion gases (200°) are withdrawn from the flue gas duct to analyse gases like ammonia, (NH_3), HCl and hydrogen fluoride (HF) without any condensation of moisture. Apart from these three gases NO, SO_2, CO, N_2O and NO_2 are also measured by the FTIR and for some of the gases (NO, SO_2, N_2O and CO) a comparison of the results from the various analysis systems is possible. The gas analysis system used in the laboratory tests is similar to those at the CFB boiler. This allows a comparison between the units as well.

RESULTS

Predried Pulp and Paper Sludge

The results from burning the pre-dried sludge (Sludge 1) are given in Figures 6-8. Figure 6 focuses on the nitrogen compounds. Table 1 shows that the nitrogen content in Sludge 1 (1.34%) is much higher (15 times) than that of the wood pellets (0.09%). This increase in the amount of nitrogen when feeding sludge into the boiler is reflected in a subsequent increase of various nitrogen-containing species in the stack, as seen in Figure 6, mainly as NO, and to some extent N_2O, but not as NO_2 or NH_3. The trends for NO and N_2O are verified by the independent analysers. NO is better analysed with the chemiluminescence instrument, while N_2O is better represented by FTIR. This is because the cross-sensitivities arising from CO, CO_2, H_2O and SO_2 are better eliminated in the FTIR than by a standard analyser. Also sulphur and chlorine are present in higher concentrations in the sludge than in the pellets. No actions, like lime supply to the furnace or hydrated lime to the bag filter, were taken to capture these species and they end up

as emissions, Figure 7, 8. However, calcium is supplied with the ash (Table 1), corresponding to a molar ratio of Ca/S between 0.8-1.3 in the three tests, and a mass balance shows that some sulphur is captured by this natural source of calcium. The increase of SO_2 in the stack is so large that the pre-calibrated range of the FTIR was exceeded. Therefore, the on-line ultraviolet (UV) analyser follows the actual SO_2 concentration better, while a deviation from this curve is seen for the FTIR at higher concentrations. There is a difference in the trends of HF and HCl, Figure 8. HF remains almost constant at levels close to the detection limit for the FTIR analyser, whereas the HCl concentration rises. CO and total hydrocarbons (HC-tot.) both indicate a reasonable degree of burnout, but the CO emission increases with the ratio of sludge. The pre-dried sludge (Sludge 1) contained a high fraction of fines, causing spikes in CO and HC-tot. that increased with the sludge ratio and resulted in a rise in the average CO emission. The CO and HC-tot. spikes are illustrated in Figure 9, showing a transient from the lowest feed rate of sludge to the highest.

Wet Pulp and Paper Sludge

Wet sludge was fed into the boiler by the sludge pump. The pump worked best with sludge from the biological treatment step used to produce Sludge 3.This sludge is similar to sludge produced in municipal sewage wastewater treatment plants [8] and forms a toothpaste-like medium that does not get stuck in the cylinders of the piston pump, the heart of the sludge feed arrangement. Fibre sludge, on the other hand, could not be fed through the sludge pump, and instead this material had to be introduced using a fuel hopper and a screw feeder, originally built for saw dust. The other sludges, mixtures of fibre and chemically precipitated sludges, were fed by the sludge pump. Their viscosity is higher than that of sludge from a biological treatment step, but not as high as that of pure fibre sludge, and some difficulties arose during feeding of these mixed sludges, such as blocking of the feeding system. However, these problems could be overcome.

The nitrogen content of wet sludge (Sludge 2,4,5,6) is similar (approx. 0.5%) and much less than in the dried sludge (Sludge 1). This lower nitrogen content in combination with lower feed ratios of wet sludge leads to a smaller increase of the NO emission, Figure 10. Wet sludge 3 has the highest nitrogen content and resulted in the largest increase of NO. In general, the N_2O emissions are low, Figure 11. The increase in N_2O due to wet sludge follows a similar pattern as that of NO, largest increase for sludge 3 and much less for the others. The emissions of the two remaining nitrogen species, NO_2 and NH_3, Figure 12 and 13, are very low and not changing with the sludge feed ratios. The next species of interest is HCl, Figure 14. The largest increase of HCl was measured in the case of fibre sludge. This increase has no coupling to the higher chlorine content of the sludge, Table 1. Another aspect of the HCl emission is related to the sludge 4 and 5. Two test series were performed, the only difference being the use of ironaluminiumsulphate (AVR) as precipitation agent in the first test and polyaluminiumchloride (PAC) in the second. This leads to an increase in the chlorine concentration in the sludge with a factor of 5, Table 1 and higher levels of HCl in the stack. The consequence of changing precipitation agent was not important, though, since the reference level without a chlorine

containing precipitation agent is very low. There is also an influence from the alkali metals, potassium (K) and sodium (Na), as indicated in the lower emissions with sludge 3 in spite of higher chlorine content than that from sludge 5 when PAC was used. Table 1 reveals that both K and Na are present in higher concentrations in the ash from sludge 3, and these species can result in the formation of the salts KCl and NaCl, preventing the chloride from being emitted as HCl.

The SO_2 emissions are shown in Figure 15. The high sulphur content of the sludges 4 and 5 correlates well with the large increase of its SO_2 emission. The SO_2 emissions are very similar in the two test series with sludge 4 and 5 despite the non-sulphur precipitation agent used in the second series. This means that the dominant sulphur source is the wastewater process itself and the choice of precipitation agent is of minor importance when the pulp and paper process produces concentrations of sulphur in the sludge above 2% on dry basis. The second highest sulphur content is found in sludge 3. Despite some calcium added with the ash, an increase of the emission cannot be avoided, Figure 15. The influence of natural addition of calcium with the fuel ash is seen for the sludge 2. The sulphur concentration in the fuel is twice as high as in the fibre sludge (Sludge 6), Table 1, but the emission of SO_2 is lower for sludge 2 thanks to the high Ca/S molar ratio of 5. The fibre sludge (Sludge 6) only has a Ca/S molar ratio of 1.4. Obviously, the Ca content in the ash has to be taken into account when discussing the effect of sulphur content in the sludge and the emission of SO_2. This aspect favours the use of fluidised beds over grate combustors, since in fluidised bed boilers sulphur can be captured in the combustion process.

In contrast to the dry sludge, the wet sludge does not cause any spikes of CO and total hydrocarbons in the exiting flue gases. The reason is that the sludge is fed as a cake that is smoothly added into the particle seal of the boiler ((4) Figure 1), serving as a pre-combustion chamber, and then further to the main combustion chamber. The dry sludge, on the other hand, is fed into the furnace through the standard fuel chute ((7) Figure 1), where fines are entrained by the combustion gas. Wet sludge combustion with wood pellets as base fuel is not only free from spikes of CO and hydrocarbons but also the average levels of these gases are low, Figures 16,17. The total hydrocarbon concentration is at the lower limit of the analyser (≈ 1 ppm), and the CO concentrations are below 20 mg /m^3_n. Also the concentration of HF was on the limit of the resolution of the FTIR analyser (≈ 1 ppm). As a matter of fact, a slight decrease of the HF concentration recorded may be linked to an unknown cross-sensitivity in the FTIR analyser, Figure 18.

Tests in the Laboratory Unit

The tests in the laboratory unit were carried out with one fuel at the time. The influence of higher nitrogen, sulphur and chlorine contents in the fuel in relation to the "clean" wood pellets should therefore be more clearly seen than in the corresponding tests in the CFB boiler where no tests with 100% sludge were carried out. As illustrated in Figures 19-21, many of the trends, seen in the large-scale tests, are confirmed in the laboratory unit: 1) The NOx emission increases when substituting wood pellets with sludge, Figure 19. Sludge 3 with the highest nitrogen content leads to the highest NOx emission also in the laboratory unit. 2) For sulphur the highest

concentration was found in the sludge 4 and 5, where the two sludges tested gave high and similar sulphur emissions, Figure 20. The influence of changing the precipitation agent in the wastewater cleaning plant was small also in the laboratory unit. There is almost no difference in SO_2 emissions and a measurable increase of the HCl emission with PAC produced sludge but from a low level, Figure 21.

CONCLUSIONS

The following conclusions can be made:

- Six pulp&paper mill sludges of various origin and type have been burned together with wood pellets in a CFB boiler. The combustion was carried out without problem.

- Feeding of the sludge into the furnace could be a major problem in connection to combustion, but such problems can be avoided using suitable fuel feed systems.

- A sludge pump is one possibility to feed mechanical dewatered sludge, especially if the sludge is produced in a biological cleaning step, but such a pump does not work properly with sludge that mainly consists of fibres.

- Pre-dried sludge may give rise to spikes of CO and hydrocarbon emissions if the fuel contains too large a fraction of fines. In such cases attention has to be paid to the method of fuel feeding.

- The content of sulphur, nitrogen and chlorine in the sludge influences the emissions markedly when sludge is co-combusted with a "clean" base fuel, such as wood pellets.

- All sludges tested contain higher concentrations of nitrogen than the wood pellets. The NO emission dominates among the four nitrogen species measured (NO, NO_2, N_2O, NH_3) and increases with the ratio of sludge.

- All sludges contain higher concentrations of sulphur than wood pellets. This leads to higher emissions of SO_2 at higher feed ratios of sludge. The calcium content in the sludge may mitigate this effect, as demonstrated by sludge 2. In most cases this will not be sufficient to prevent the SO_2 emission to reach a level above the legalisation level, and active actions like lime addition to the fluidized bed or hydrated lime to a bag filter are required.

- Substitution of ironaluminiumsulphate (AVR) as precipitation agent with a species not containing sulphur like polyaluminiumchloride (PAC) did not significantly change the sulphur content of the sludge.

- The use of PAC in sludge 5 increases the chlorine content of the sludge. This has a marginal effect on the HCl emission.

- Some aspects of substitution of wood pellets with sludge were confirmed in a laboratory-scale reactor.

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TABLES

TABLE 1. Origin, type and properties of the pulp and paper sludges.

Sludge / Type of sludge / Precipitation agent	Sludge 1 Dried, $F_{(1)}$,$B_{(3)}$	Sludge 2 Wet, $F_{(1)}$,$C_{(2)}$	Sludge 3 Wet, $F_{(1)}$,$B_{(3)}$	Sludge 4 Wet, $F_{(1)}$,$C_{(2)}$ $AVR_{(4)}$	Sludge 5 Wet, $F_{(1)}$,$C_{(2)}$ $PAC_{(5)}$	Sludge 6 Wet, $F_{(1)}$,	Wood pellets
Proximate analysis							
Water (wt-%, raw)	26.2	73.4	82.2	77.6	76.7	72.4	8.3
Ash (wt-%, dry)	24.8	21.0	15.1	12.3	12.7	2.3	0.45
Combustibles (wt-%, dry)	56.6	21.0	15.2	19.6	20.4	27.0	91.2
Volatiles (wt-%, daf)	77.4	87.0	82.9	72.1	72.7	81.8	81.8
Ultimate analysis (wt-%, daf)							
C	55.0	48.6	48.8	52.4	51.8	52.2	50.3
H	6.2	6.6	6.5	6.3	6.4	6.5	6.1
O	36.3	43.8	40.0	38.3	38.8	40.7	43.5
S	1.10	0.58	1.42	2.41	2.28	0.26	0.01
N	1.34	0.48	3.31	0.55	0.62	0.44	0.09
Cl	0.08	0.03	0.02	0.009	0.05	0.007	0.01
Lower heating value (MJ/kg)							
Hu, $daf_{(6)}$	19.99	16.72	18.34	19.26	20.09	19.57	18.81
Hu, $raw_{(7)}$	9.68	1.6	0.73	1.85	2.18	3.47	16.90
Ash analysis (g/kg dry ash)							
K	9.4	3.5	17.7	2.8	6.3	9.5	82
Na	8.6	7.9	32.6	8.4	11.7	108	6.7
Al	125	185	125	263	317	84.1	12.2
Si	239	86.8	100	110	64.9	116	79.7
Fe	27.4	25.1	96.4	20.1	8.6	23.3	20.9
Ca	35.9	151	44.3	7	7.1	94.6	164
Mg	14.7	4.4	38.6	20.6	21.7	10.9	26.4
P	5.3	4.4	25.7	3.4	3.6	14.2	12.7
Ti	19.8	8.8	1.2	28.9	18.9	4.8	0.7
Ba	0.4	0.2	1.7	0.4	0.4	1.2	2.4

(1)= fibre sludge, (2)= chemical precipitated sludge, (3)= biological sludge, (4)= Ironaluminiumsulphate, (5)= Polyaluminiumchloride, (6)= dry and ash free, (7)=as received

TABLE 2. Operating conditions for the tests with pre-dried sludge and pure wood pellets

| Sludge / Type of sludge / Test number	Sludge 1 Dried, $F_{(1)}$,$C_{(2)}$ 2	Sludge 1 Dried, $F_{(1)}$,$C_{(2)}$ 1	Sludge 1 Dried, $F_{(1)}$,$C_{(2)}$ 3	Wood pellets 1
waste fraction $_{(3)}$,%	13.4	25.3	52.9	0.0
load, MW_{th}	6.3	6.2	6.1	6.7
bed temp., °C (bottom)	851	851	851	849
bed temp., °C (top)	860	854	857	861
exit temp. of after burning chamber, °C	828	825	829	865
total riser pressure drop, kPa	6.4	6.5	6.6	6.3
Calcium addition molar ratio Ca/S	0.00	0.00	0.00	0.00
Ca/S with Ca in fuel included	1.44	1.01	0.76	2.81
excess air ratio	1.26	1.28	1.25	1.19
primary air flow/ total air flow,%	59	58	59	55
superficial flue gas velocity at top of riser U_{top}, m/s	5.3	5.4	5.5	5.3

(1)= fibre sludge, (2)= chemical precipitated sludge, (3)= dry matter(waste)/dry matter (mixture)

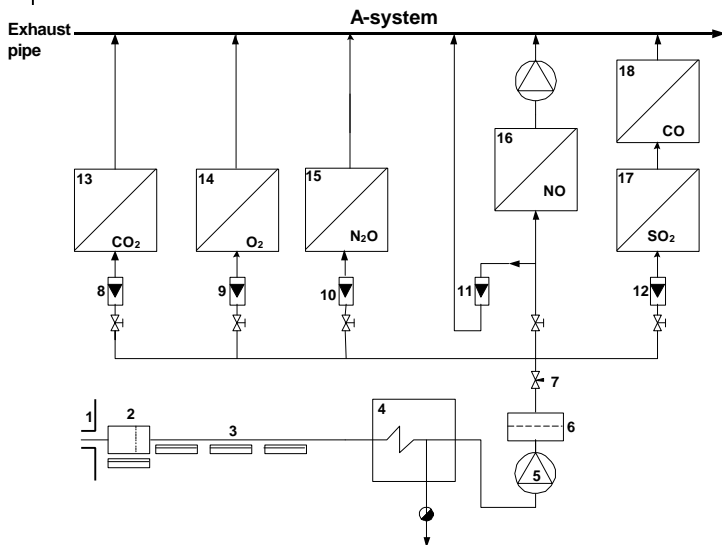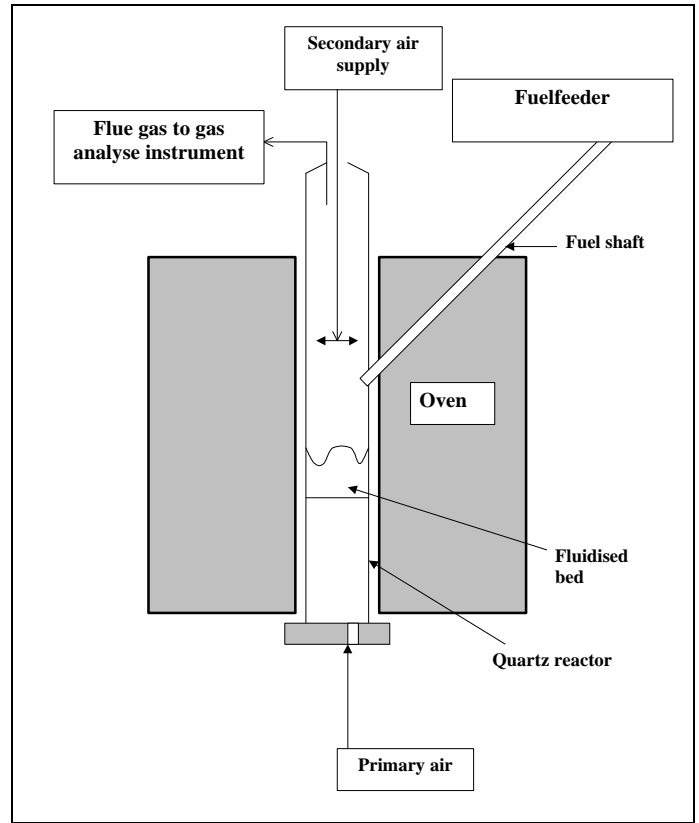**TABLE 3. Operating conditions for the tests with mechanical dewatered sludge.**

Sludge	Sludge 2	Sludge 2	Sludge 2	Sludge 3	Sludge 3	Sludge 4	Sludge 4	Sludge 5	Sludge 5	Sludge 6
Type of sludge	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},B_{(3)}$	Wet, $F_{(1)},B_{(3)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)},C_{(2)}$	Wet, $F_{(1)}$
Precipitation agent						$AVR_{(4)}$	$AVR_{(4)}$	$PAC_{(5)}$	$PAC_{(5)}$	
Test number	1	2_1	2_2	1	2_2	1	2	3	4	1
waste fraction $_{(6)}$, %	14.6	7.9	8.0	10.3	5.8	12.2	6.0	14.8	7.6	16.0
load, MW_{th}	6.5	6.3	6.3	6.2	6.2	6.5	6.6	5.9	6.0	6.3
bed temp., °C (bottom)	853	850	848	847	850	847	847	848	850	849
bed temp., °C (top)	871	859	847	872	871	873	867	859	856	859
exit temp. of after burning chamber, °C	880	858	859	835	832	859	869	827	815	878
total riser pressure drop, kPa	6.3	6.3	6.4	6.4	6.3	6.5	6.2	6.2	6.2	6.3
Calcium addition molar ratio Ca/S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca/S with Ca in fuel included	5.16	5.14	4.97	0.70	1.18	0.25	0.25	0.24	0.42	1.40
excess air ratio	1.23	1.21	1.20	1.22	1.24	1.19	1.21	1.24	1.25	1.21
primary air flow/ total air flow,%	57	58	58	59	58	58	49	58	59	58
superficial flue gas velocity at top of riser U_{top}, m/s	5.7	5.4	5.2	5.2	4.8	5.6	6.0	5.1	5.0	5.7

(1)= fibre sludge, (2)= chemical precipitated sludge, (3)= biological sludge, (4)= Ironaluminiumsulphate, (5)= Polyaluminiumchloride, (6)= dry matter(waste)/dry matter (mixture)
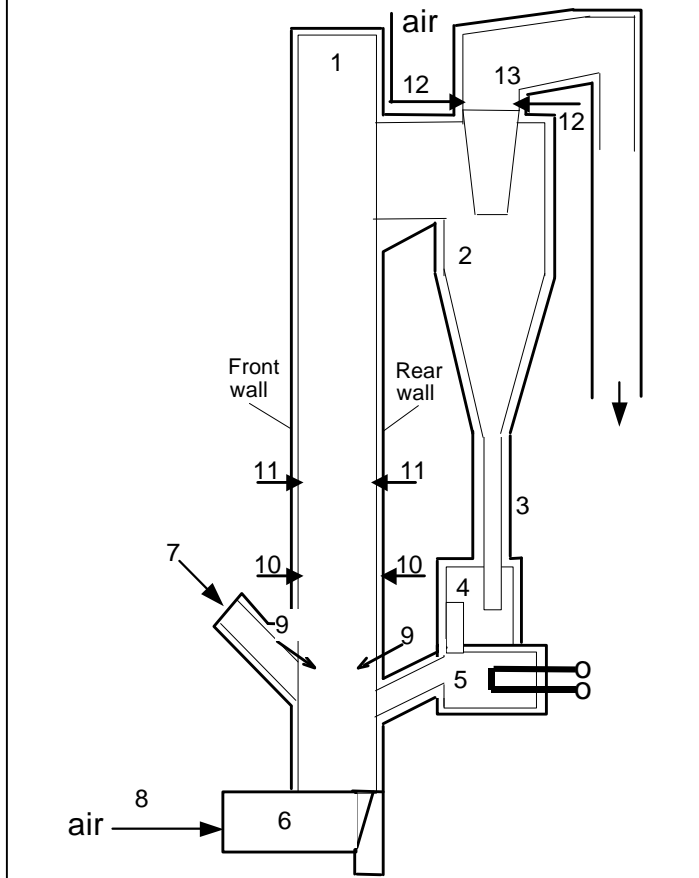
Figure 1. The 12-MW$_{th}$ CFB boiler at Chalmers University of Technology. (1) combustion chamber, (2) cyclone, (3) particle return leg, (4) particle seal, (5) heat exchanger, (6) windbox, (7) fuel feed chute, (8) primary air supply, (9) secondary air to 2.1meter, (10) secondary air to 3.7 meter, (11) secondary air to 5.4 meter, (12) secondary air addition after cyclone, (13) exit duct cyclone.

Figure 2. The laboratory reactor at SP, Swedish National Testing and Research Institute.

Figure 3. Gas analysis system A used for analysis of flue gas in the stack. (1) gas sampling probe; (2) heated ceramic filter; (3) heated gas sampling line; (4) moisture removal; (5) gas sampling pump; (6) safety filter; (7) mass flow controller, total flow; (8-12) individual volumetric flow controllers; (13) CO$_2$ analyser; (14) O$_2$ analyser; (15) N$_2$O analyser; (16) NO analyser; (17) SO$_2$ analyser (18) CO analyser
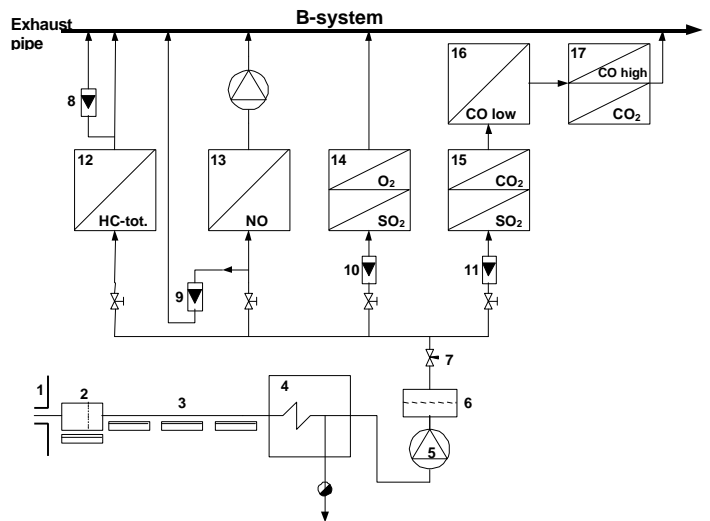
Figure 4. Gas analysis system B normally used for analysis of flue gases from the combustion chamber (1) gas sampling probe; (2) heated ceramic filter; (3) heated gas sampling line; (4) moisture removal; (5) gas sampling pump; (6) safety filter; (7) total mass flow controller; (8-11) individual volumetric flow controllers; (12) HC-tot. analyser; (13) NO analyser; (14) SO$_2$ and O$_2$ analyser; (15) SO$_2$ and CO analyser; (16) CO-low analyser; (17) CO$_2$ and CO-high analyser
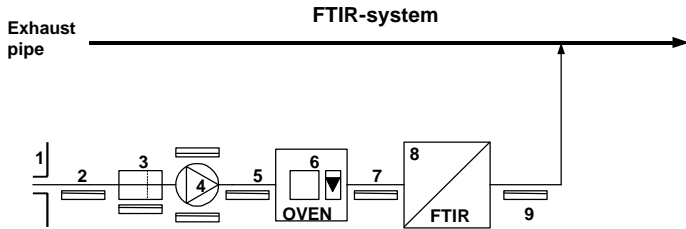
Figure 5. Gas analysis system (FTIR) used for analysis of flue gases from the combustion chamber (1) gas sampling probe with ceramic filter; (2), (5), (7), (9) heated gas sampling line; (3) heated ceramic filter; (4) heated gas sampling pump;(6) oven with filter and volumetric flow controller; (8) Fourier transformed infra-red analyzer.
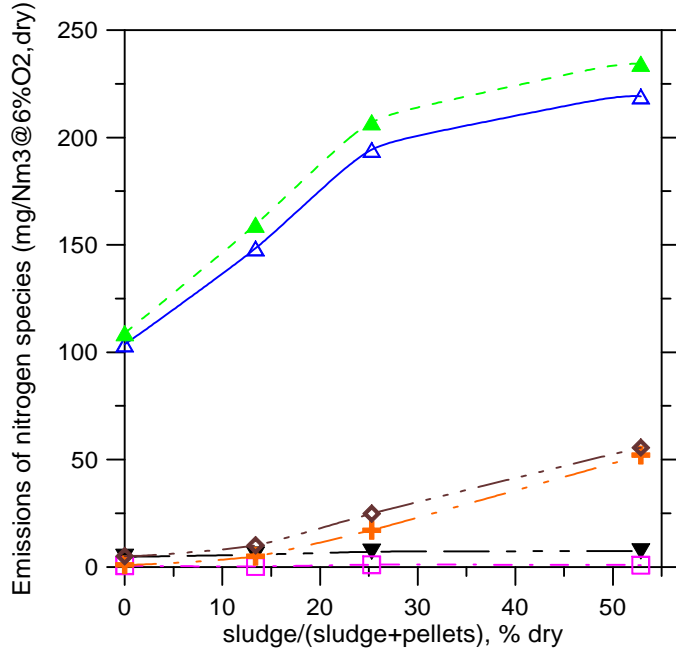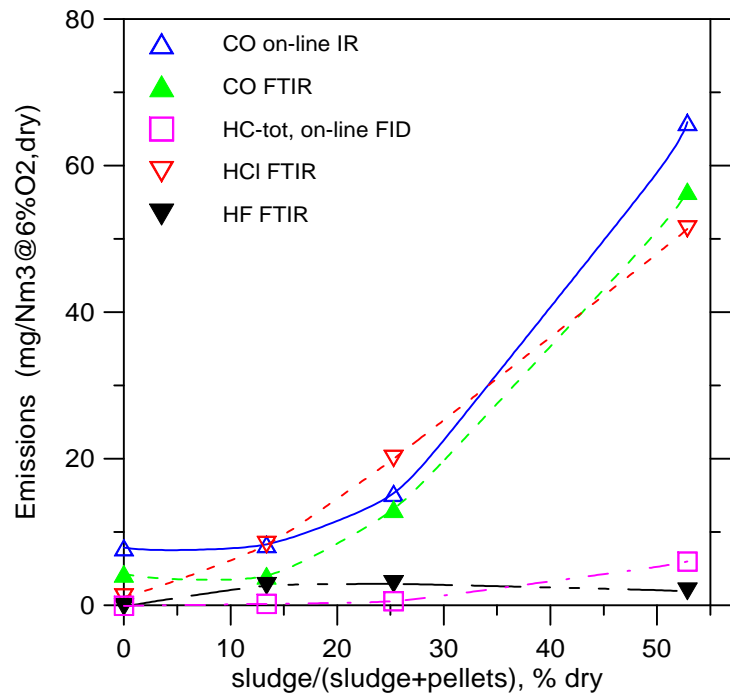

Figure 6. Influence of co-combustion of dry pulp and paper sludge (Sludge 1) with wood pellets on the emissions of nitrogen compounds. NO and NO_2 emissions expressed as mg NO_2/Nm^3@6%O_2, dry
△ **NO chemiluminescence,** ▲ **NO FTIR,** ▼ **NO_2 FTIR**
□ **NH_3 FTIR** ✚ **N_2O on-line IR** ◇ **N_2O FTIR**
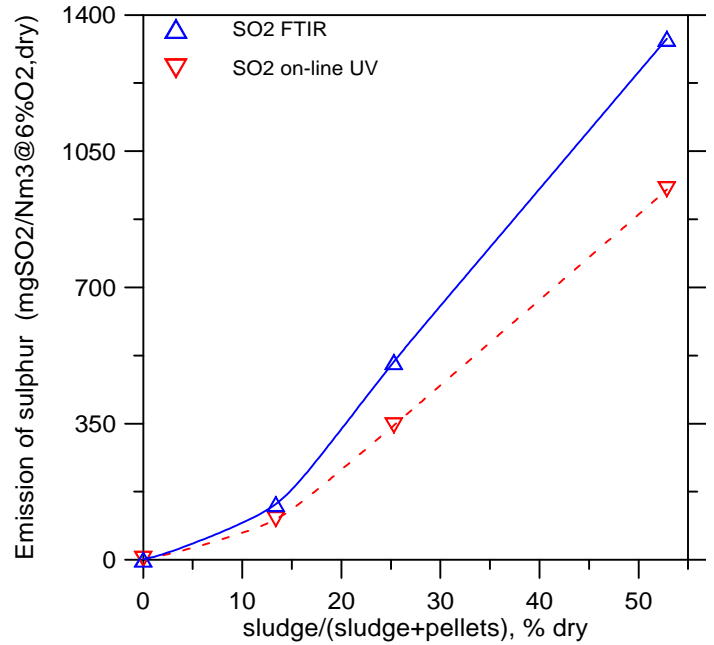
Figure 7. Influence of co-combustion of dry pulp and paper sludge (Sludge 1) with wood pellets on the emission of SO_2.

Figure 8. Influence of co-combustion of dry pulp and paper sludge (Sludge 1) with wood pellets on the emissions of CO, total hydrocarbons (HC-tot.), HCl and HF.
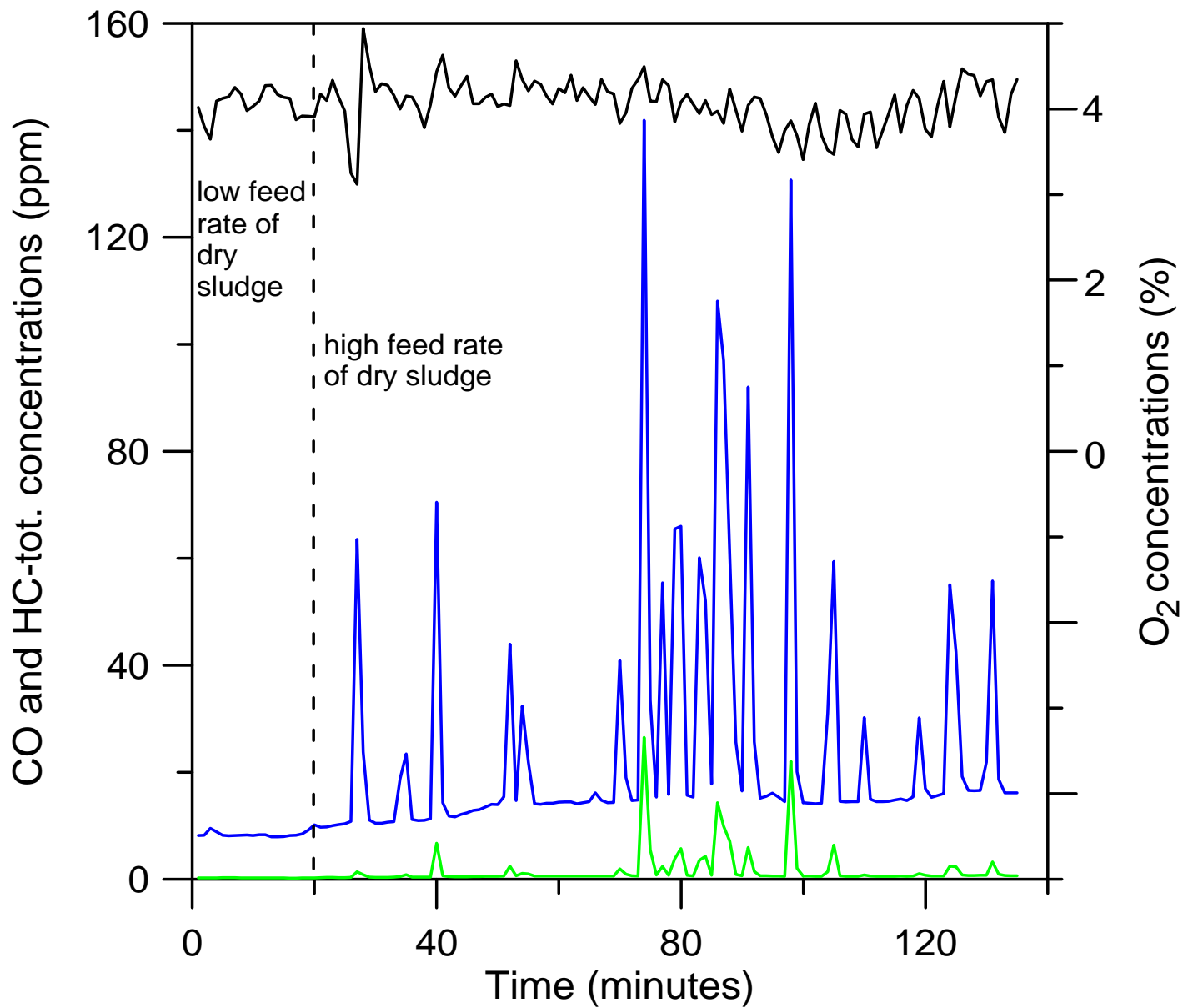
Figure 9. Influence of the increase (at t=20 minutes) of the ratio of dry pulp and paper sludge on the emissions of CO (blue) and total hydrocarbons (green). Black: oxygen concentrations
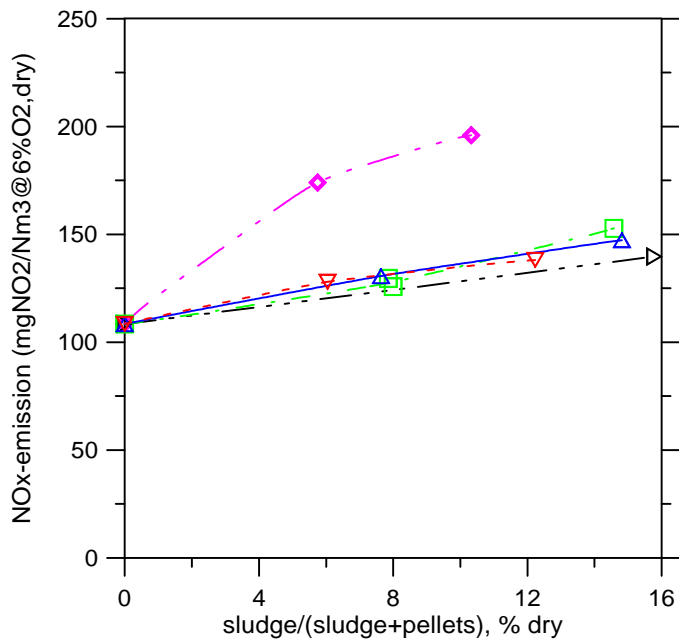
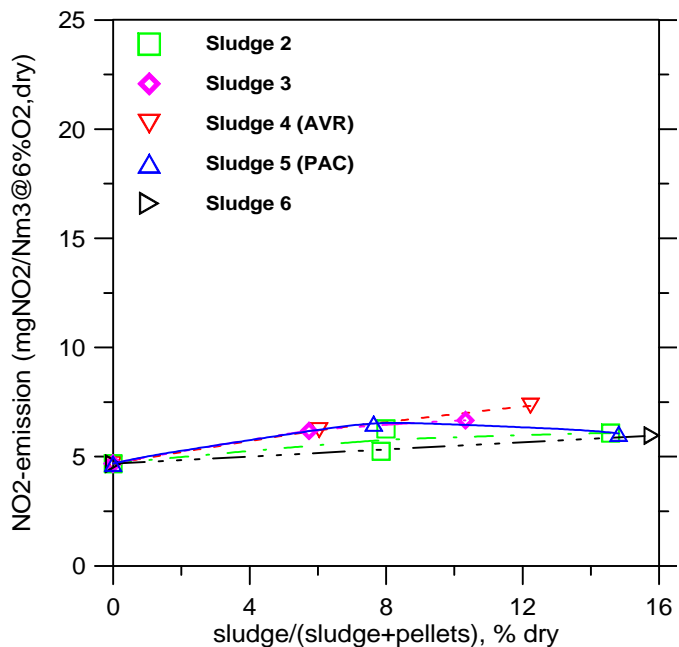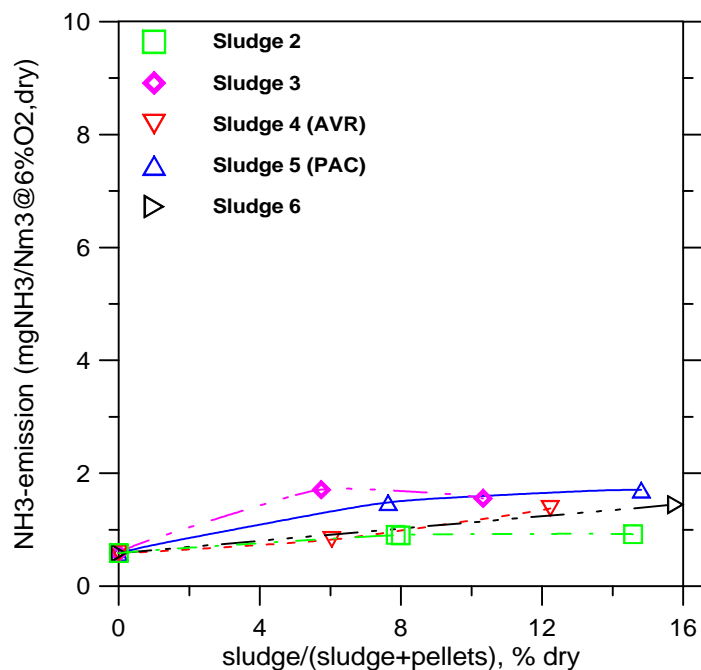**Figure 10. Influence of co-combustion of mechanically dewatered pulp and paper sludge with wood pellets on the emissions of NOx . ☐ Sludge 2, ◆ Sludge 3, ▽ Sludge 4 (AVR), △ Sludge 5 (PAC), ▷ Sludge 6**
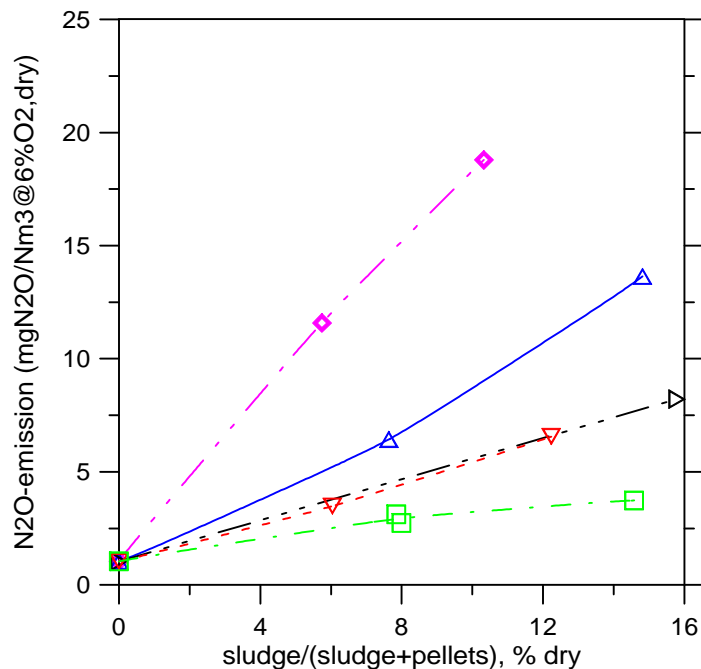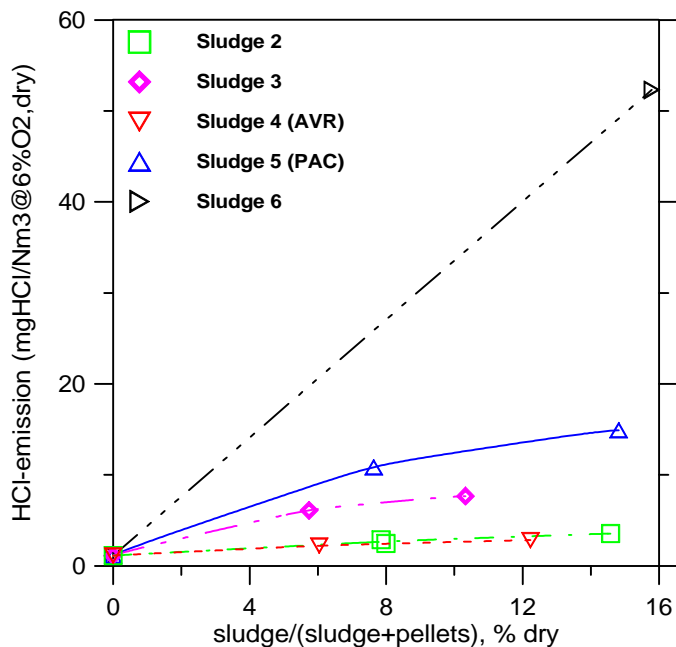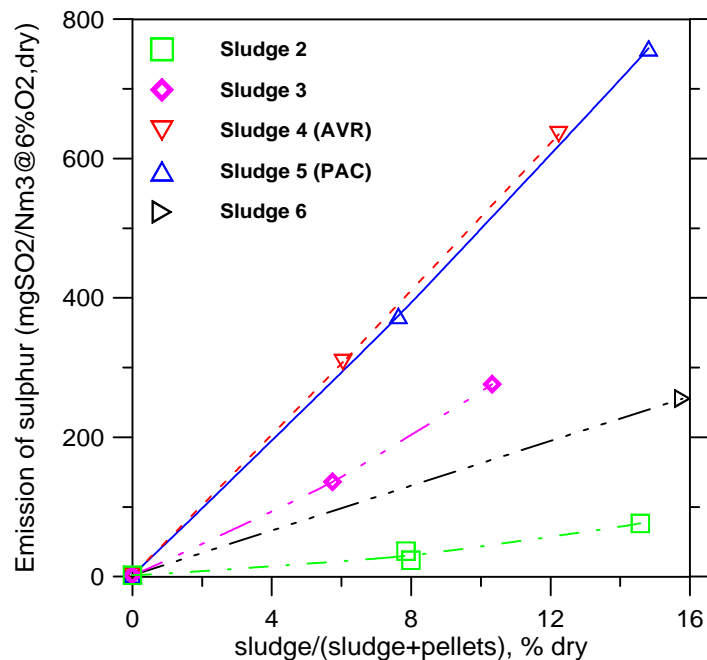

Figure 11. Influence of co-combustion of mechanically dewatered pulp and paper sludge with wood pellets on the emissions of N_2O. ☐ Sludge 2, ◆ Sludge 3, ▽ Sludge 4 (AVR), △ Sludge 5 (PAC), ▷ Sludge 6

Figure 12. Influence of co-combustion of mechanically dewatered pulp and paper sludge with wood pellets on the emissions of NO_2.

Figure 13. Influence of co-combustion of mechanically dewatered pulp and paper sludge with wood pellets on the emissions of NH_3.

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Figure 14. Influence of co-combustion of mechanically de-watered pulp and paper sludge with wood pellets on the emissions of HCl.

Figure 15. Influence of co-combustion of mechanically de-watered pulp and paper sludge with wood pellets on the emissions of SO$_2$.
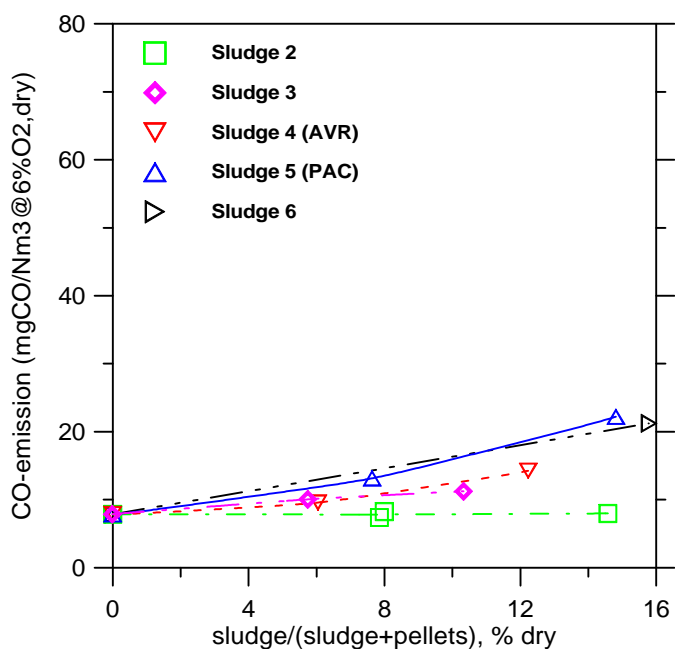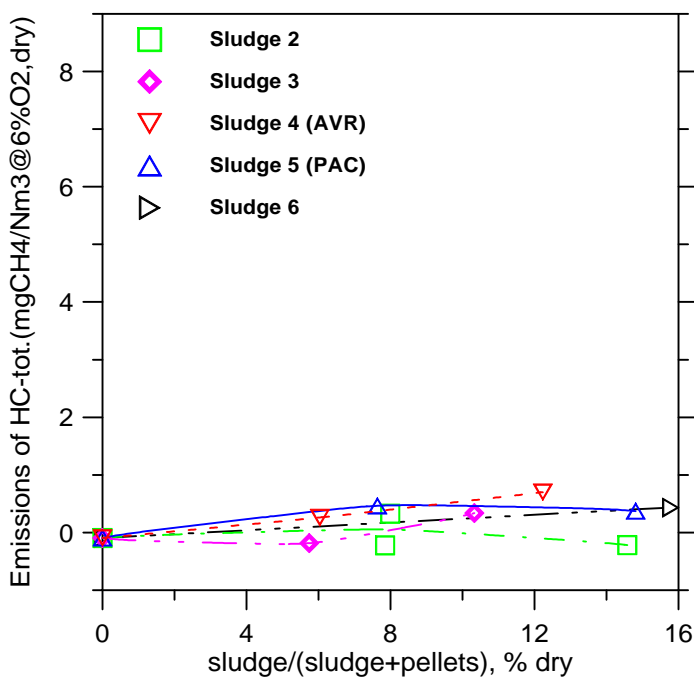

Figure 16. Influence of co-combustion of mechanically de-watered pulp and paper sludge with wood pellets on the emissions of CO.

Figure 17. Influence of co-combustion of mechanically de-watered pulp and paper sludge with wood pellets on the emissions of total hydrocarbons (HC-tot.).
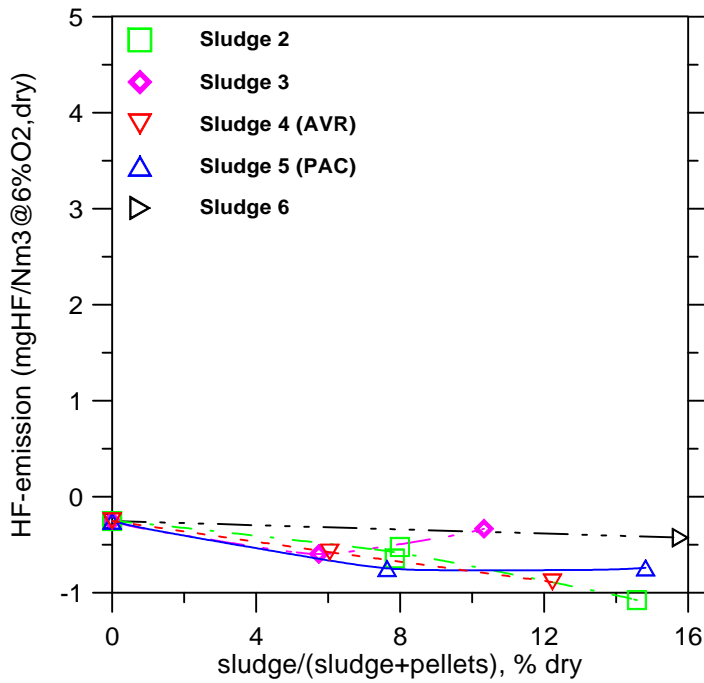
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Figure 18. Influence of co-combustion of mechanically de-watered pulp and paper sludge with wood pellets on the emissions of HF.
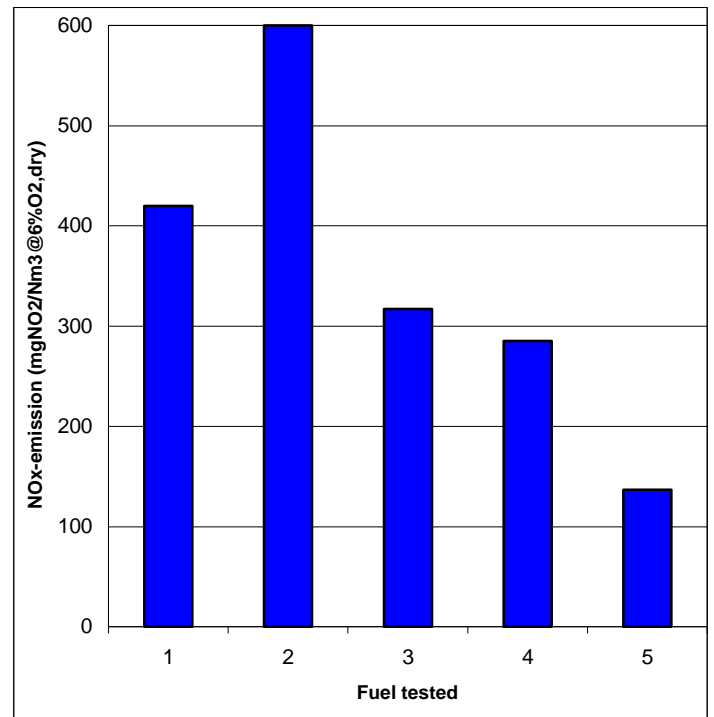

Figure 19. NOx emission from tests performed in the laboratory unit. Fuels tested: 1. Sludge 2; 2. Sludge 3; 3. Sludge 4 (AVR); 4. Sludge 5 (PAC); 5 Wood pellets.
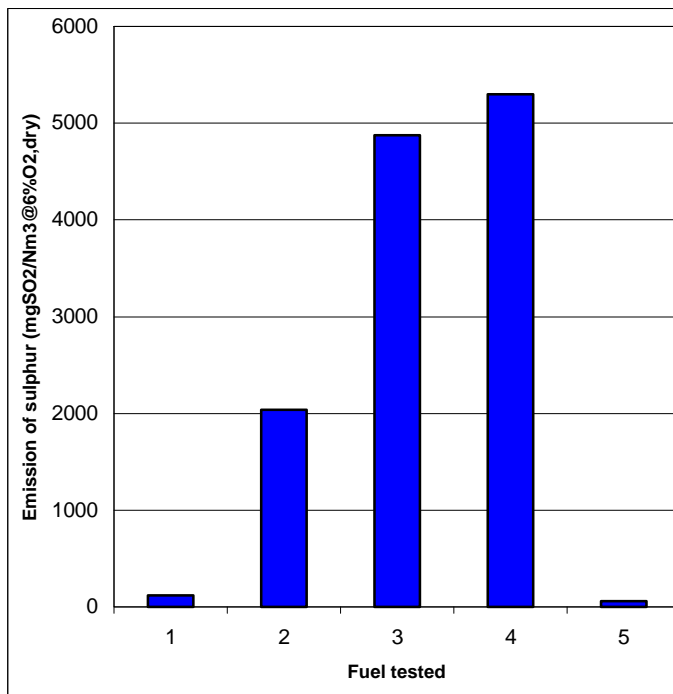

Figure 20. SO$_2$ emission from tests performed in the laboratory unit. Fuels tested: 1. Sludge 2; 2. Sludge 3; 3. Sludge 4 (AVR); 4. Sludge 5 (PAC); 5 Wood pellets.
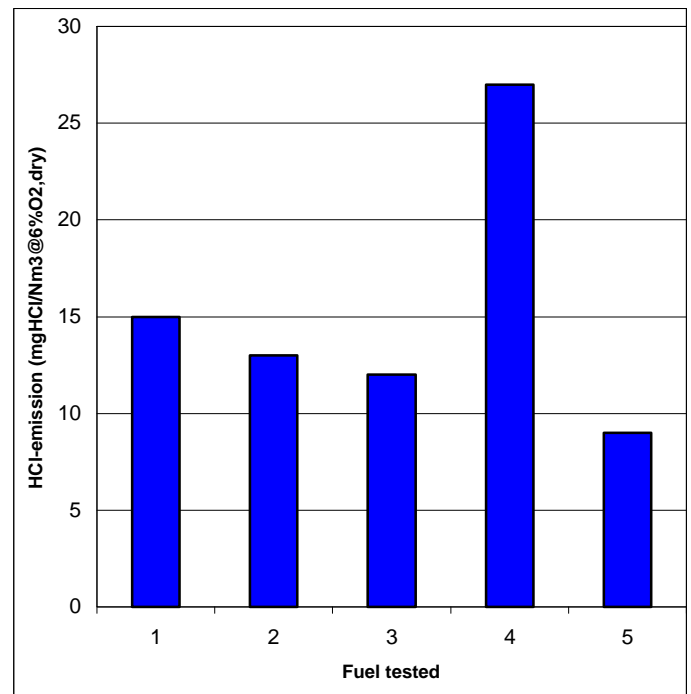

Figure 21. HCl emission from tests performed in the laboratory unit. Fuels tested: 1. Sludge 2; 2. Sludge 3; 3. Sludge 4 (AVR); 4. Sludge 5 (PAC); 5 Wood pellets.