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CO-COMBUSTION OF DRIED SEWAGE SLUDGE AND COAL/WOOD IN CFB-- A SEARCH FOR FACTORS INFLUENCING EMISSIONS

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Abstract
Co-combustion of sewage sludge with either coal or wood as base fuels was investigated in two CFB units, one laboratory scale combustor and one pilot scale boiler of industrial size. The investigation was focused on general combustion performance and flue gas emissions. It was found that co-combustion with dry sewage sludge can be carried out within the range investigated (a sludge fraction of less than 50% of the energy supply) without any problems. The NO emission could be high because of the high nitrogen content of the sludge, but it was shown that the reduction in the CFB is also high and the resulting emission is only moderate. The same is the case with the other emissions recorded (CO, N_2O). Sulphur emissions from combustion of the sludge is a consequence of sulphur components originating from the organic part of the sludge (sulphur-containing proteins for example).

Introduction

Co-combustion of biomass or wastes with coal or other primary fuels has many potential advantages: the effective emission of CO_2 is reduced by replacing some coal with waste, efficient utilization of the energy in waste by converting it to electricity in the coal power station and, of course, the primary purpose—destruction of waste. There are also some potential risks: some biofuels may lead to slagging and fouling in the combustor or bed agglomeration in a fluidised bed, some wastes lead to enhanced emissions of heavy metals and, finally, an augmentation of the gaseous emissions may occur, especially during combustion of sewage sludge. If sewage sludge is to be used as an additional fuel, investigation of the related emissions becomes particularly important because of the large content of nitrogen in the fuel, which in a hypothetical extreme case (if all nitrogen were converted to NO) could give rise to an additional emission of 100 to 200 ppm NO per % (energy) of dry sludge added.

Fluidized bed combustion is probably the most advantageous method available for co-combustion because of its fuel flexibility and the possibility to influence the processes of formation and destruction of emissions. Therefore the present work is dedicated to a study of the emission performance of co-combustion of dried sludge in circulating fluidised bed (CFB). In a previous work [1] the influence of air supply on flue-gas pollutant concentrations (emissions) was investigated and few in-furnace measurements were presented. In-furnace measurements of gaseous concentration give a picture of formation and reduction processes in the boiler, and hence, an idea of the processes yielding the emissions. Therefore, the present publication complements previous data and shows concentration variations along the gas path. In addition, some comments will be made regarding the influence of bed material and ashes on the emissions.

Experimental background

Facilities

The backbone of the present investigation is the 12 MW_{th} CFB combustor located at Chalmers Technical University (CTH), Figure 1. 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 (8). The circulating solids are separated in the cyclone (2) and transported through the particle return leg (3), the loop seal and the external heat exchanger back into the combustion chamber. Primary combustion air (9) is supplied to the wind box (7) below the gas distributor, whereas secondary air (9) may be added either into the combustion chamber or downstream of the cyclone (11). The exit duct is refractory lined and serves as an after-burner chamber (12).
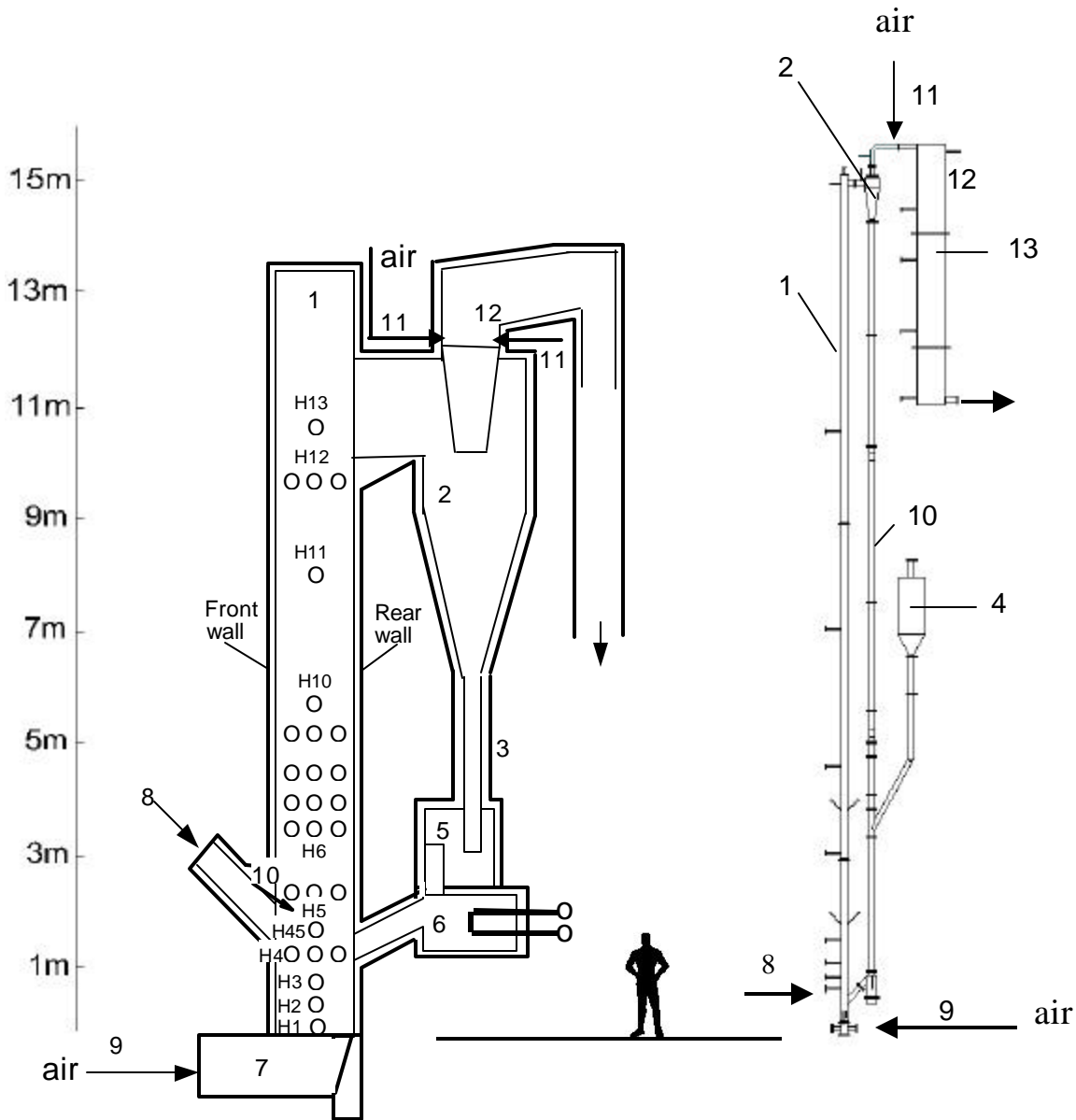
Fig. 1: The CFB test facilities at CTH in Göteborg (left) and at TUHH in Hamburg (right): (1) combustion chamber, (2) cyclone, (3) particle return line, (4) bed material hopper, (5) particle seal, (6) heat exchanger, (7) windbox, (8) fuel feed, (9) primary air supply, (10) air into the fuel feed chute, (11) secondary air addition after cyclone, (12) after-burner chamber, (13) probe for flue gas extraction. Measurement ports (H1 to H13) on the right boiler wall indicated

The dimensions of this unit are close to a commercial scale. This means that results obtained are transferable to industrial units. Investigations in the boiler are complemented by measurements in the pilot scale unit operated at the Technical University Hamburg-Harburg (TUHH). This pilot scale unit consists of a cylindrical combustion chamber with a diameter of 0.1 m (cross-section area 0.008 m^2) and a total height of 15 m. Although this device is significantly smaller in diameter than the CTH boiler, it has been shown in a previous investigation [2] that the emissions are practically the same as those from the CTH boiler if suitable similarity rules are obeyed in the operation.

Both units are equipped with gas analysis systems, calibrated daily, for monitoring both local in-furnace and flue gas concentrations of O_2, CO_2, CO, SO_2, NO, N_2O. The CTH boiler is part of the heating system of the university and can therefore be operated continuously during the winter season. It is possible to operate sufficiently long periods under constant conditions to obtain steady state composition of the bed material. This cannot be done in the Hamburg unit, which is operated for

measurement campaigns of between 12 and 16 hours, starting early in the morning to avoid three shift operation. The TUHH unit is electrically heated during start-up until a temperature of 600 $^{\circ}$C is attained 2 to 3 hours from start. Each operation condition is kept for about 30 minutes during which emissions are measured. The emissions are measured by gas extraction at a point inside the after-burner 1.92 m downstream of the entrance. Supplementary electrical heating can strictly control the bed temperature.

Fuels

The properties of the fuels are given in Table 1. The same fuels and the same bed materials were used in both units.

Table 1. Properties of the fuels investigated.

	Bituminous coal	Wood pellets	Sewage sludge
Proximate analysis			
Water (wt-%, raw)	8.6±1.1	9.2±0.2	19.0±5.4
Ash (wt-%, dry)	16.5±1.9	0.8±0.2	37.9±1.0
Combustibles (wt-%, dry)	83.5±1.9	99.2±0.2	62.1±1.0
Volatiles (wt-%, daf)	34.7±0.6	81.2±0.0	90.5±0.7
Ultimate analysis (wt-%, daf)			
C	82.5	50.5	53.2
H	5.0	6.0	7.1
O	9.9	43.4	30.6
S	0.90	0.02	1.90
N	1.70	0.14	7.10
Cl	0.07	0.01	0.05
Lower heating value (MJ/kg)			
Hu, daf	32.49	18.91	20.9
Hu, raw	24.58±0.9	16.78±0.05	10.05±1.04
Ash analysis (mg/kg dry ash)			
K	557±179	448±5	1820±164
Na	137±6	90±16	602±45
Al	2767±1097	178±52	18400±1341
Si	47667±14434	1000±0	48800±1789
Fe	8167±3175	568±377	73800±2863
Ca	5467±1097	1275±96	27200±1643
Mg	2366±404	193±19	4180±295
P	1733±1154	315±182	38800±1643
Ti	300±0	2875±2249	538±84

daf= dry and ash free, raw= as received

The two base fuels were bituminous coal and wood. The wood was in the form of pellets, but this is not important in the present context, except that it gives the wood fuel a fairly homogeneous composition. The sludge was a sewage sludge, dried after primary digestion to a residual water content of about 20%. The ultimate analysis shows that the oxygen content of the sludge is high (30%), almost as high as that of the wood. The very high nitrogen content of the sewage sludge should also be noted, as well as the very low one for wood. The high sulfur content of the sludge originates from sulfur-containing compounds used in the waste water treatment plant for flocculation of the sludge. The iron content of the sludge is also very high. The combination of the high iron content of the ash and the high ash content of sludge lead to a substantial increase of the feed of iron to the boiler.

Experimental procedure

The units were operated under the same operation conditions. The related data are given in Table 2.

Table 2. Operation conditions

	Coal, CTH	Coal, TUHH	Wood, CTH
Load, MW	6.5±0.1	0.031±0.002	6.5±0.1
Bed temp. °C (bottom)	841±0	852±3	841±0
Bed temp. °C (top)	855±1	852±3	857±3
Exit temp, after-burner chamber, °C	772±4 (2)	847±3	797±1(782)(1)
Excess air-ratio	1.23±0.01	1.22±0.006	1.23±0.01
Combustor air_ratio	1.05±0.01	1.05±0	1.04±0.01
Superficial velocity, m/s	5.3±0.4	4.97±0.06	4.6±0.1(4.1)(2)
Calcium addition, Ca/S molar ratio	2.3±0.05	2.13±0.1	1.9±0.1(0)(1)
Ca/S with Ca in fuel included	2.6±0.2	2.3±0.2	2.5±0.1(0)(1)

(1) without sludge, (2) trend, increasing with amount of sludge

The ranges of variation in Table 2 are those from test to test. The primary air was added to the bottom air-distributor in the CTH unit, except for a small amount of air used to improve fuel injection. Otherwise no air was added to the riser or to the cyclone. The remaining air, needed to achieve the total excess air-ratio, was introduced downstream of the cyclone in the entrance to the afterburner chamber. This mode of operation has been called "advanced staging" and was maintained in all tests shown in this paper. The influence of air supply on co-combustion of sludge has been presented in a separate paper [1].

As seen from the table, the conditions have been quite stable despite the large differences between the fuels. The only trend noticed was a slight increase in temperature of the afterburner chamber as sludge was added. Also the limestone, added to reduce sulphur emissions, could not be kept constant between the tests because the exact sulphur content of the sludge was not known at the time of the experiments.

Results and discussion
The results are presented in Figures 2 to 4. Conclusions based on these figures will be presented below. Similar data, not related to sludge but to other fuels, have been given in previous studies [2].

Progress of combustion
The progress of combustion is most conveniently observed in the variations of the concentrations of O_2 and CO along the gas path, Figure 2. The oxygen concentration is low in the bottom part of the combustor. This reveals that a substantial part of the combustion takes place there. At higher levels in the combustor the concentration is higher than at the bottom, which appears contradictory, since essentially all air supplied to the furnace enters equally distributed through the air distributor through the bottom of the combustion chamber. The reason may be an uneven distribution of air consumption by combustion in the bottom part, especially in the large combustor, leading to a gradual mixing of the oxygen supplied by the air into the central parts of the combustor at higher levels. The concentration differences are fairly small, however, and the CO concentration falls from the bottom towards the exit smoothly, as expected. The concentration of CO, and hence of unburned gases, is high in the lower part of the combustor—in the percentage range. The gases further burn in the cyclone and, after secondary air injection, in the exit combustion duct, the "afterburner".

The introduction of sludge, even in such a high fraction as 50%, did not change the combustion patterns significantly. In general, the differences between coal and wood (later burn-out and higher concentrations of combustible gases in the case of wood) are more significant than the differences occurring during combustion of mixtures. The CO emission is similar to what has been seen before, e.g. [3]: higher when coal is involved (with or without sludge) and low for wood (with or without sludge). In both cases, the emission level is acceptably low, Figure 4f.

The same type of measurements in the TUHH unit show similar results with one exception: as noted previously [2], mixing is better in the narrow tube at TUHH than in the wider boiler at CTH and the concentrations of unburned gases are lower in the TUHH combustor. At the exit, however, the emissions become quite similar in the two units, Figure 4f.

<u>Nitrogen oxides</u>

The addition of sludge shows itself as a dominant (order of magnitude) increase in the concentration of NO in the furnace, Figure 3. Never before we have observed so high concentrations (3500 ppm of NO). However, the reduction along the gas path is substantial and the concentration in the gas leaving the boiler is not extremely high: the resulting conversion of fuel nitrogen to NO is only a few percent, Figure 4. Figure 4 represents the emission data in two ways: as fuel nitrogen conversion and as emission in mg/m^3_n. The emissions from combustion of pure wood and coal are almost the same despite the differences in fuel nitrogen content (Table 1). Consequently the conversion of fuel nitrogen to NO is much higher for wood than for coal. This has been explained previously [3] as an effect of the higher char concentration in the combustor in the case of coal and, as a consequence, of the higher reduction of the NO formed. When the sludge concentration increases, the NO emission also increases. However, the conversion is about constant (coal-sludge) or even decreasing (wood-sludge).
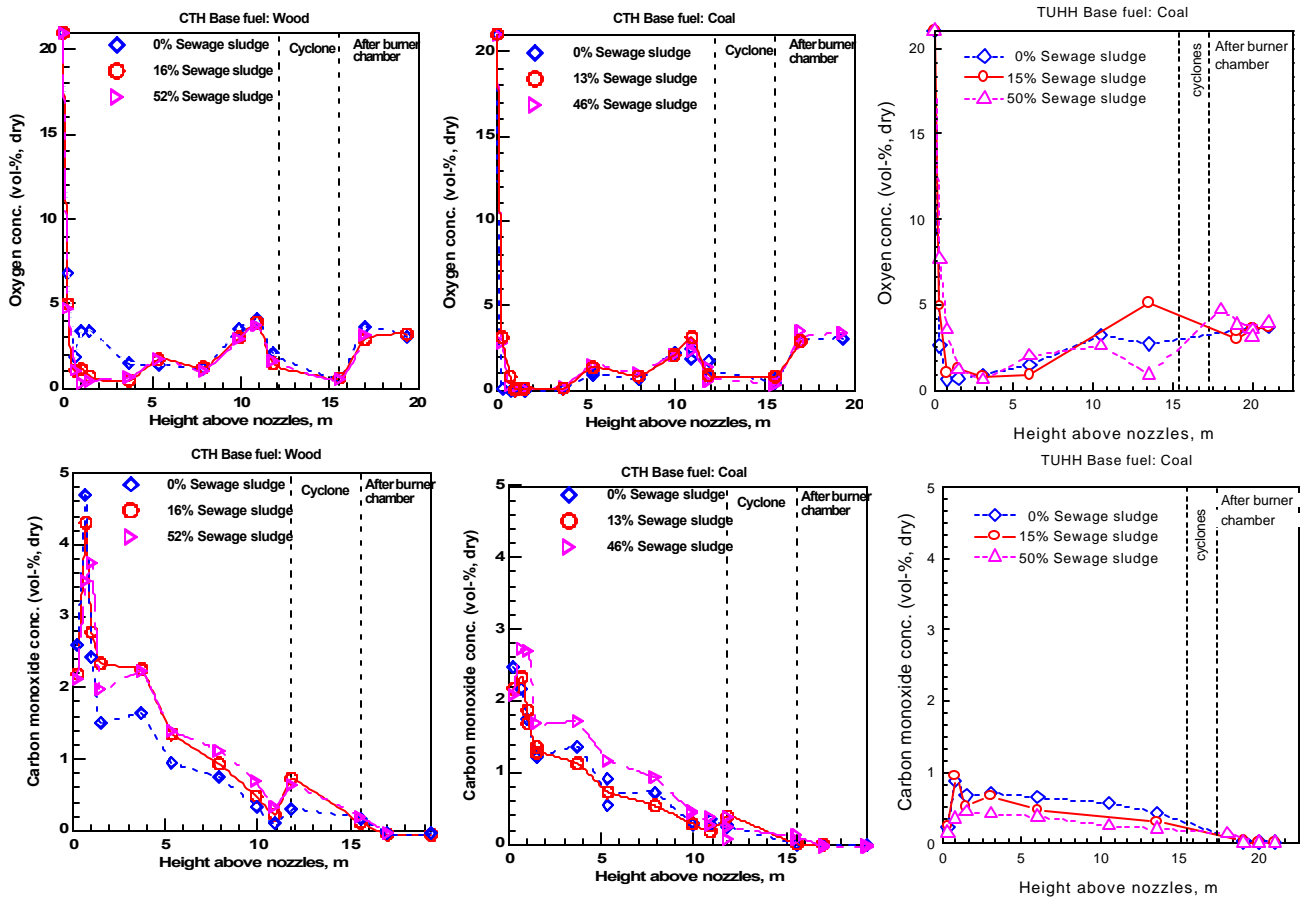

Figure 2. Gas concentrations of O_2 and CO on the centre-line of the combustion chamber of the CTH and TUHH units during co-combustion with wood and coal (CTH) and coal (TUHH) as base fuels.
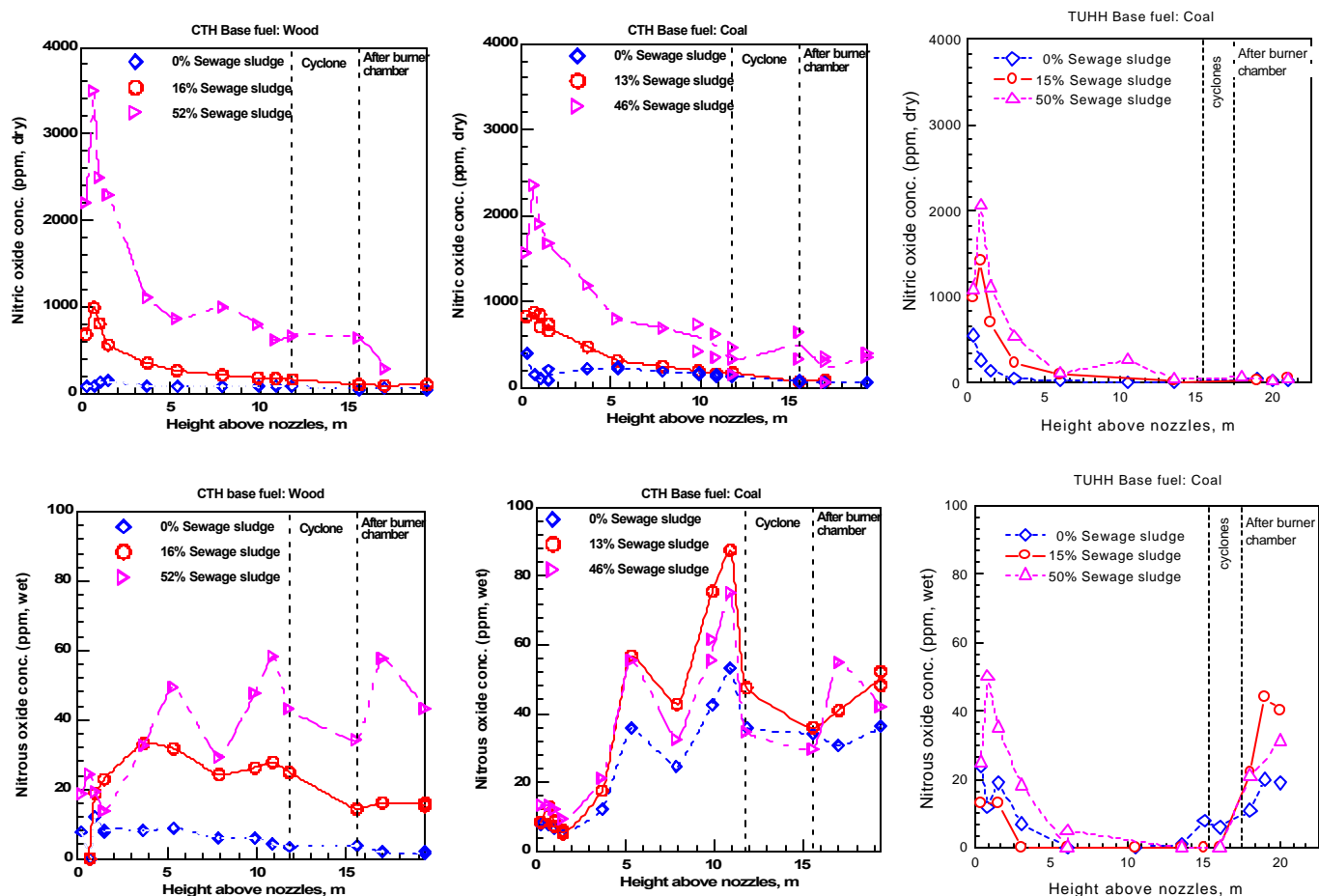
Figure 3. Concentrations of NO and N₂O on the centre-line of the combustion chamber of the CTH and TUHH units during co-combustion with wood and coal (CTH) and coal (TUHH) as base fuels.

This can not any more be explained by an increase of the content of char in the riser, since it is likely, judging from the fuel composition (Table 1), that the char concentration decreases as the sludge fraction increases. The remaining influencing factors would be the volatiles (NH_3) or the bed material (to be discussed below). At present there is no clear view on the effect of these factors. The effective conversion to NO is only a few percent, and hence 96 to 98 % are not converted to NO. This makes a small change in conversion a great change in emission, and it becomes difficult to accurately predict the emission of NO in mg/m^3_n.

The corresponding data from TUHH agree quite well with those of CTH, both emission (Figure 4) and centre-line concentration (Figure 3).

The rather low emissions of N_2O (Figure 4) depend on two factors: the staging method applied gives low emissions and in the case of wood there is practically no emission of N_2O at all. During co-combustion with sludge the emission rises slightly, but the values are still low, both with coal and with wood as base fuels. The conversion of fuel nitrogen to N_2O is also only a few percent. The rising concentrations of N_2O with height in the furnace, seen in Figure 3, are typical compared to what has been measured previously for coal. The agreement with TUHH is fair, but there is a peculiar behaviour in the TUHH in-furnace N_2O concentrations (Figure 3) that needs further investigation.

Sulphur emission

Sulphur is added by sludge and coal but not by wood. Therefore it is interesting to compare the performance of limestone addition to co-combustion with either coal or wood as base fuels. Unfortunately it was not possible to add the exact amount of limestone, as explained above, and the Ca/S ratios were different during operation with the two base fuels. Therefore, to reduce the effect of the different ratios, in Figure 4 the results are expressed as lime efficiency. The measurements show that a sulphur capture of more than 90% is possible at Ca/S=2.6 with coal, independent of the sludge
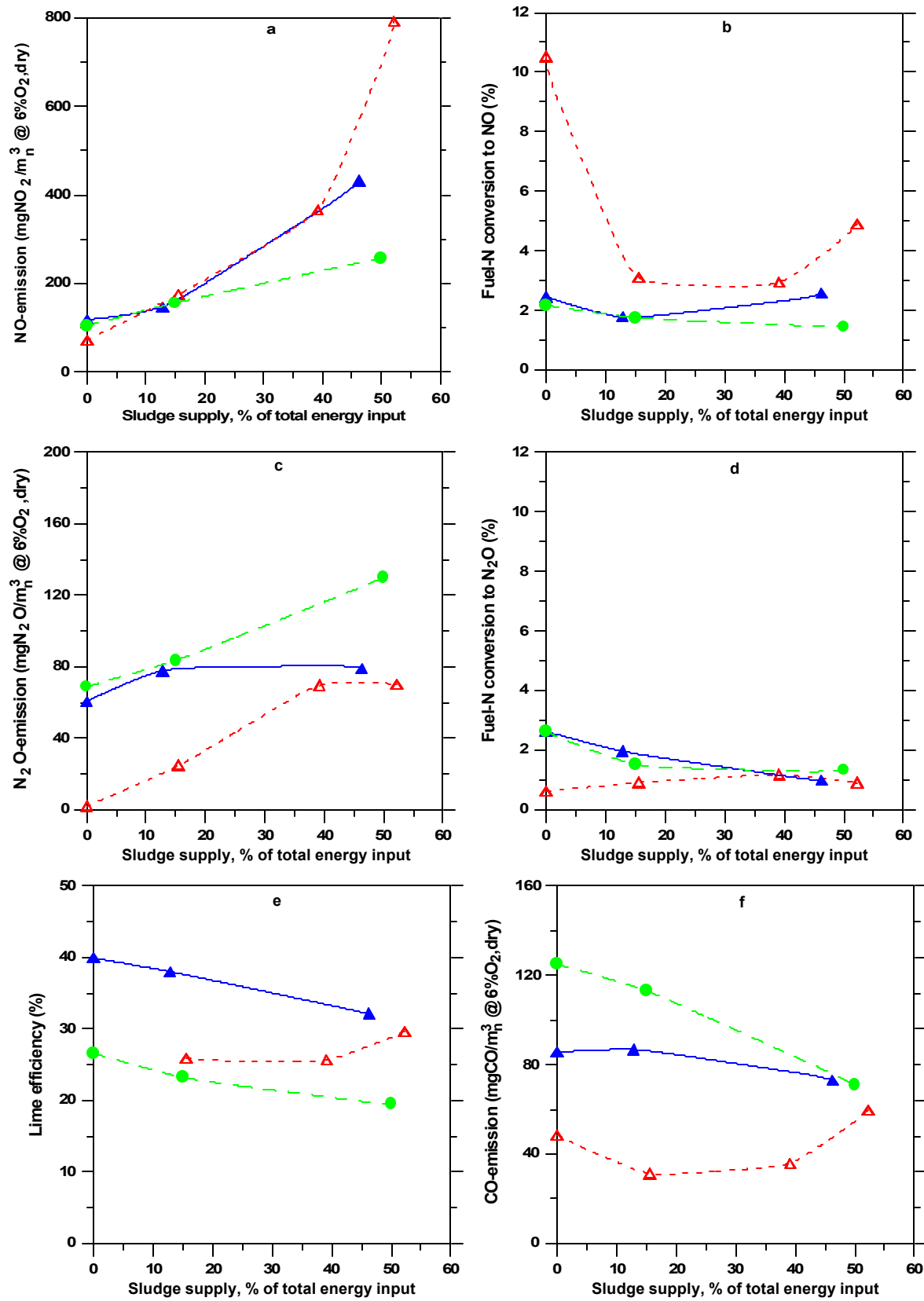
Figure 4. Emissions of NO (a), N_2O (c), CO (f) and conversion of fuel nitrogen to NO (b) and N_2O (d) and lime efficiency (e)

Symbols:

CTH: Co-combustion of coal and sludge   CTH: Co-combustion of wood and sludge

TUHH: Co-combustion of coal and sludge

fraction. There is no reason to believe that a sulphur capture above 90% cannot be attained for co-combustion with wood also, but in this case, for some unknown reason, the lime utilisation is lower than for coal, Figure 4, and a somewhat higher Ca/S ratio would be needed to attain the same level of sulphur capture as for coal. These differences are not important in practice, since the obvious conclusion is as follows: in the case of coal, desulphurisation with limestone is carried out also in the absence of sludge addition, and the sulphur content of the sludge is only a marginal contribution. If wood would be used as base fuel, it could be more convenient to remove the SO_2 in the flue gas by a dry scrubbing system in the bag house filter for example.

Bed material

The sludge contains considerable quantities of iron in the form of oxide or iron converted into oxide in the bed. This can be observed visually, since the ashes are coloured red. Iron oxide serves as a catalyst for oxidation of ammonia (released from the fuel) to NO. The catalytic effect has been clearly illustrated by addition of iron oxide (Fe_3O_4 with an average size of 20 μm) powder to the cyclone during combustion of coal, Figure 5. The figure shows the weight of the hopper during addition of iron oxide at a constant feed rate of 485 kg/h or 2.8 kmol Fe/h between the hours 1.42 and 2.30. The feed rate was 4.8 times higher than the iron supply by the ashes of the sludge. The effect was seen as an immediate rise in the concentration of NO from about 100ppm to about 300 ppm. When the addition of iron oxide was stopped, the NO emission gradually returned to the original level as the iron disappeared. This experience cannot be readily applied to the sludge combustion case, but the existence of catalytically active species in the material added with the sludge may affect the emission of NO from co-combustion with sludge.
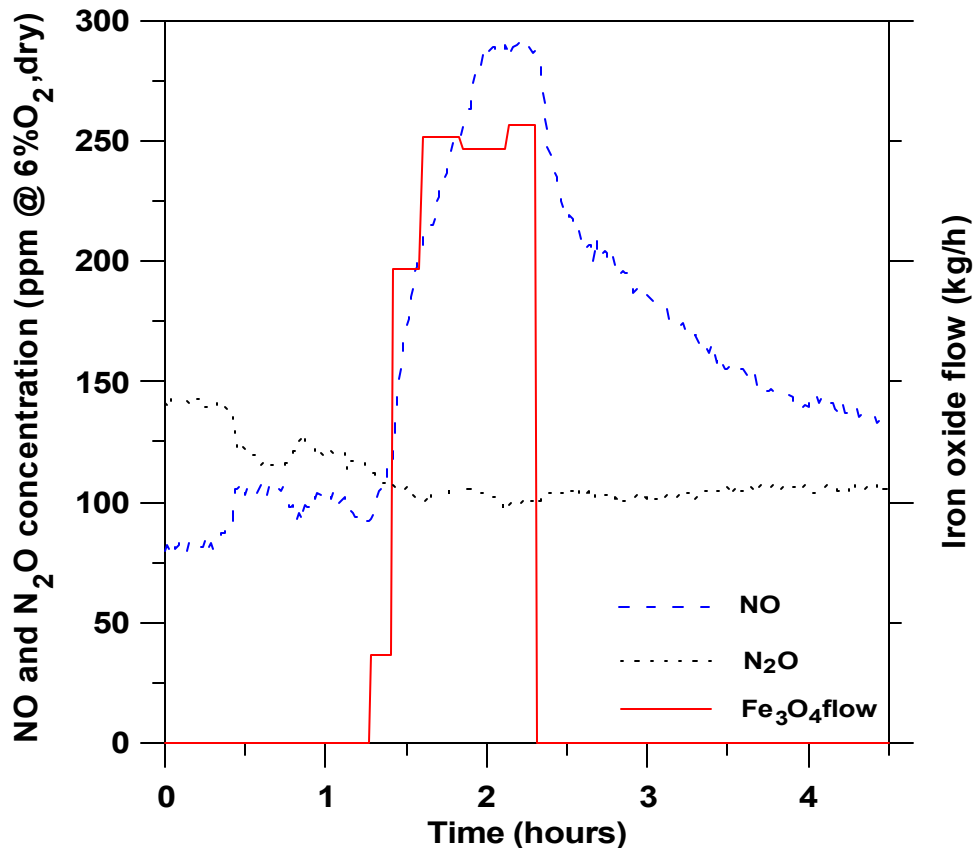

Figure 5 Addition of iron oxide (Fe_3O_4) to the combustion chamber during coal combustion at normal operating conditions. Between t=1.42 and t=2.30 the average iron oxide addition is 485 kg/h which is equal to 2.8 kmoles/h

Tests in two quite different plants with dry sewage sludge as an additional fuel to either coal or wood have been carried out with similar results in the two plants.

Dried sewage sludge can be handled together with the base fuels without any technical problem. The co-combustion performed well, and only small differences from the over-all performance of the base fuels were observed, despite fractions of added fuel of up to 50% (energy).

Sewage sludge contains large quantities of nitrogen, and high concentrations of NO were observed in the CFB combustors. However, the reduction was also high in the combustor, and the emission of NO was moderate. A low and almost constant conversion of fuel nitrogen to NO resulted in a rising NO emission with increasing fraction of sludge. The conversion is affected by char and volatiles in the combustor and probably also catalytically by iron oxide from the ashes.

The emission of nitrous oxide, N_2O, was low, possibly a result of the present mode of air supply in the CFB combustor, "advanced" air staging.

A sulphur capture efficiency of more than 90% can be attained with a reasonable addition of limestone. For low sulphur base-fuels, such as wood, sulphur capture is not needed for the base fuel However, additional sulphur supply with sludge cannot be avoided and flue gas treatment by a dry scrubbing system in the bag house filter should be tested as an alternative to lime addition to the combustor.

Hence co-combustion with dried sewage sludge is a feasible procedure as far as handling, combustion and gaseous emissions are concerned. The importance of heavy metals in the sludge remains to be assessed.

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