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Co-Combustion of Sewage Sludge with Wood/Coal in a Circulating Fluidized Bed Boiler- A Study of Gaseous Emissions

L.-E. Åmand, B. Leckner
Department of Energy Conversion, Chalmers University of Technology
SE-41296 Göteborg, Sweden

Abstract

Reduction of emissions of NO and N_2O from co-combustion of wet or dried sewage sludge with coal or wood is investigated. This is motivated by the high nitrogen content in sewage sludge that may give rise to high emissions. An advanced air-staging method for combustion in circulating fluidised bed is applied. It is shown that with fluidised bed combustion the emissions are low as long as the sludge fraction is not too high, (say less than 25%), the conversion of fuel nitrogen to NO or N_2O is only a few percent. However, air staging is not efficient for high volatile fuels and any air supply method can be applied in such a case, in contrast to the situation during combustion of coal.

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 a coal power station and, of course, the primary purpose—destruction of waste. There are also potential risks: some biofuels may lead to slagging and fouling in the combustor or to bed agglomeration in a fluidized 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 of dried sewage sludge (if all nitrogen were converted to NO) could give rise to an additional emission of 100 to 200 ppm NO per % energy of 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. There are several potentially important factors to investigate. Here we focus on three aspects: 1) What is the difference between coal and wood as base fuels for co-combustion? 2) What is the difference between dry and wet sludge with respect to emissions? 3) What is the impact on the air supply system? In order to limit the presentation we treat in the first place emissions of nitrogen oxides (NO and N_2O).

A more detailed description of the background of the present work is found in [1].

Air Supply and Emissions

Previous work [2] has shown that the arrangement of the air supply has a significant influence on the emissions. Considerable reduction of emissions of especially N_2O but also NO, while leaving sulphur capture and combustion performance relatively un-affected, was found if the

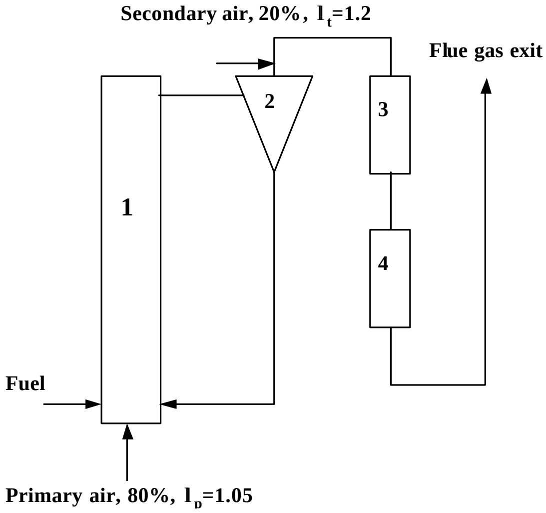

Fig. 1. CFB combustor showing "advanced" air staging. 1 Combustion chamber, 2 Particle separator, cyclone, 3 Afterburner, 4 Convection path.

air supply is staged in such a way that primary air is introduced under near-stoichiometric condition and final air for completion of combustion is added in the particle-free space downstream of the cyclone in a circulating fluidized bed (CFB) combustor, Fig. 1.

The arrangement shown in Fig. 1 is called "advanced" staging in contrast to "normal" staging, where about 60% of the combustion air is introduced from the bottom and the remaining 40% through air nozzles located 2-3 m from the bottom of the combustion chamber. In addition, there is an extreme arrangement called "no-staging", where all air is introduced from the bottom.

Fuels and Experimental Equipment

The 12 MW CFB boiler at Chalmers University of Technology (CTH) was used for the experimental runs. Some tests referred to were made in a laboratory CFB at the Technical University of Hamburg-Harburg (TUHH) [1]. Both devices, although different in size, look in principle like the scheme shown in Fig. 1. The combustion chamber of the Chalmers boiler (1) has a square cross-section of about 2.25 m^2 and a height of 13.6 m. Fuel is fed from the bottom. The circulating bed material is recirculated through a cyclone (2) back to the combustion chamber, whereas the combustion gases enter an "afterburner", a small combustion chamber where secondary air may be introduced for burnout of the remaining unburned gases. Downstream there is a cooler, the "convection path" where the gases are cooled down to 150 °C before cleaning in a secondary cyclone and a bag filter. This is where the gas concentrations the "emissions" are measured by means of a comprehensive set of gas analyzers, some of which also serve for in-furnace measurements.

Table 1. Fuel properties

	Bituminous coal	Wood pellets	Sewage sludge, dry	Sewage sludge, wet
Proximate analysis				
Water (wt-%, raw)	8.6±1.1	9.2±0.2	19.0±5.4	70.4
Ash (wt-%, dry)	16.5±1.9	0.8±0.2	37.9±1.0	52.2
Combustibles (wt-%, dry)	83.5±1.9	99.2±0.2	62.1±1.0	47.8
Volatiles (wt-%, daf)	34.7±0.6	81.2±0.0	90.5±0.7	94.1
Ultimate analysis *(wt-%, daf)*				
C	82.5	50.5	53.2	52.1
H	5.0	6.0	7.1	7.1
O	9.9	43.4	30.6	33.2
S	0.90	0.02	1.90	1.60
N	1.70	0.14	7.10	6.10
Cl	0.07	0.01	0.05	0.09
Lower heating value *(MJ/kg)*				
H_u, daf	32.49	18.91	20.9	19.9
H_u, raw	24.58±0.9	16.78±0.05	10.05±1.04	1.1

daf= dry and ash free, raw= as received

The two base fuels were bituminous coal and wood pellets. Sludge was added in quantities up to 50% of the energy content of the mixture. The sludges were dried sewage sludge with a average moisture content of 19% and mechanically de-watered sewage sludge with a moisture content of 77%. The wet sludge could only be used in minor energy fractions, as obvious from the composition of the fuels, Table 1, because of the desire to run all tests under similar operation conditions, that is, at constant temperature, see Table 2.

Results

A comparison of coal and wood pellets as base fuels during co-combustion of dried sewage sludge is seen in Fig. 2. The data reflect the properties of the fuels and the conversion of fuel nitrogen. The conversion is only a few percent for coal but may amount to 10-20% for wood as observed before [3]. Since the nitrogen content in coal is much higher than in wood, the result is that the NO emission from coal and wood in CFB are rather similar. When sludge with its high nitrogen content is added, the NO emission increases. The N_2O emission from wood is almost zero and that from coal is low because of the advanced staging strategy used. Addition of sludge makes the emissions increase, but not much and only to the low level of coal.

Table 2. Operating conditions

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

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

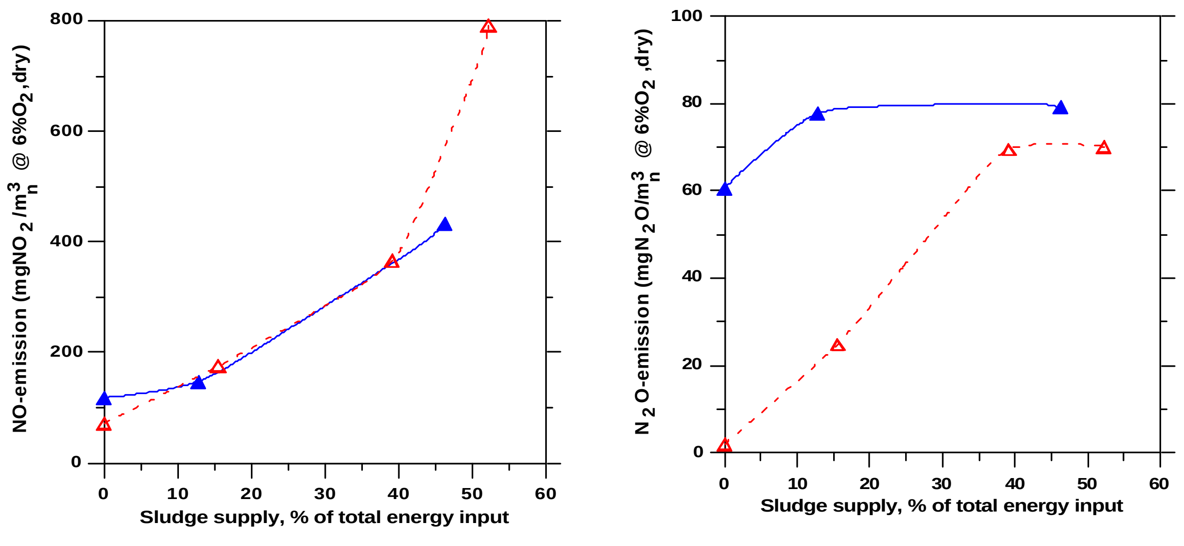

Fig. 2 Emissions of NO and N_2O during advanced air staging

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

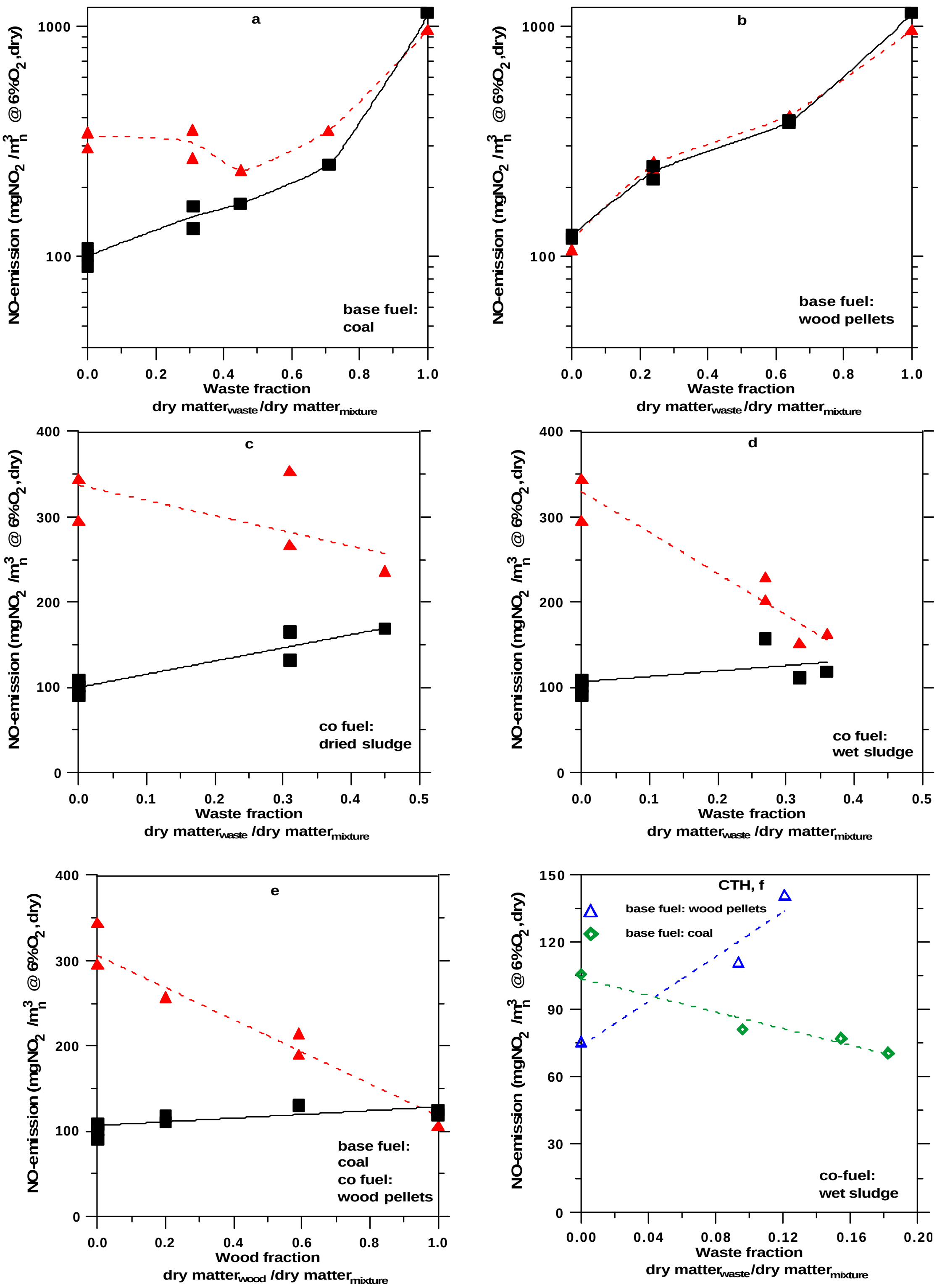

Fig. 3a-f. Influence of fuel and air staging. ▲ no-staging,■ advanced staging. Note that the horizontal scales sometimes differs and that logarithmic scales are used in some diagrams. Data are recorded on the CFB reactor at TUHH [1]. Figure 3f from data recorded in the CTH boiler

Figure 3 is based on data obtained in the laboratory combustor at TUHH operated with fuels according to Table 1 and the same conditions as in Table 2. The diagrams contain data on all three items of interest in the present comparison: base fuels coal and wood pellets, dried and wet sludge and different air supply conditions. Figure 3f, which is for wet sewage sludge co-

combusted with coal or wood in the Chalmers boiler, can be compared with the corresponding data in Fig. 3d for advanced air staging. In general there is a qualitative agreement between emission data from the two plants, similar to what has been observed in other comparisons [4].

The influence of staging is clearly seen in the comparison between the pure fuels in Fig. 3. Especially for coal the staging gives a considerable reduction of the emission of NO, Figs 3a, 3c, 3d and 3e at waste fraction=0 but in the case of wood the impact is less important, Fig 3b at waste fraction=0 and Fig 3e at wood fraction=1. In fact, on the whole the impact of air supply is rather small or negligible for high volatile fuels. Since sludge is a high volatile fuel, this means that with increasing fraction of sludge staging becomes less important. The standard explanation [3] is that the content of char in the bed is decisive for NO (and N_2O) reduction. For low volatile fuels there is a high (a few percent) concentration of char in the bed, whereas for high volatile fuels, having a small content of fixed carbon, the concentration of char in the bed is low (less than one percent). A change in the air supply to the bed (at constant temperature) affects the content of char and hence the reduction of NO. The change becomes more noticeable with a high concentration of char.

There is also an influence of fuel nitrogen content. Wood is useful for the present comparison because of its low nitrogen content. Comparing coal/dried sludge, Fig. 3a and coal/wood, Fig. 3e and in addition paying attention to wood/dried sludge, Fig3b, it becomes clear that in all cases when nitrogen is added in large quantities with the sludge the NO emission increases. The decrease in the case of coal/wood with increasing fractions of wood can be interpreted as a consequence of reduction of the total fuel nitrogen added and simultaneously of a lower reduction capacity as the char content in the bed decreases. However, this explanation does not hold for coal/wet sludge that behaves like coal/wood. The nitrogen content in wet sludge is similar (or even higher) to that in dried sludge so there is only one explanation left: this could have been an effect of volatile fuel nitrogen, which is certainly present in the other cases as well but which could be particularly strong for wet sludge because of the ammonia contained in the evaporated moisture. This effect is also seen in Fig. 3f for the CTH tests. Co-combustion of coal with wet sludge leads to a decrease of the NO emission opposite of the trend observed for dried sludge in Fig. 2. On the other hand, co-combustion of wood pellets with wet sludge leads to an increase of the NO-emission similar to the trend in Fig.2 for dried sludge. This means that the effect of ammonia in the large amounts of water supplied with the wet sludge need to be further investigated.

In Fig. 4 gas concentrations along the gas path through the combustion chamber, cyclone and afterburner show the progress of combustion and the transformation of pollutants. The oxygen concentration falls almost instantaneously in the lower part of the combustion chamber. As the quantity of primary air was stoichiometric, this behaviour reveals that almost all fuel burns in the bottom bed. The rise of oxygen concentration downstream of the cyclone shows the effect of secondary air injection. The uneven oxygen concentration between 5 and 10 m is most likely because of mixing effects, although the air was evenly supplied to the bottom air distributor with exception of some air introduced from the front with the fuel. It is remarkable how different fuel mixtures have behaved in a similar way in all cases: the progress of combustion has been similar, except for a minor difference in the case of pure wood where combustion (as has often been observed) was less intensive in the bottom bed and the oxygen concentration was higher. The concentration of CO give an indication of the progress of combustion as well as the release of volatiles. As expected, the data for wood are higher than those of coal. Also shown in Fig. 4 are the profiles of NO and N_2O. Note the differences in scale in the two sets of figures. The large scale for NO makes the exit concentrations

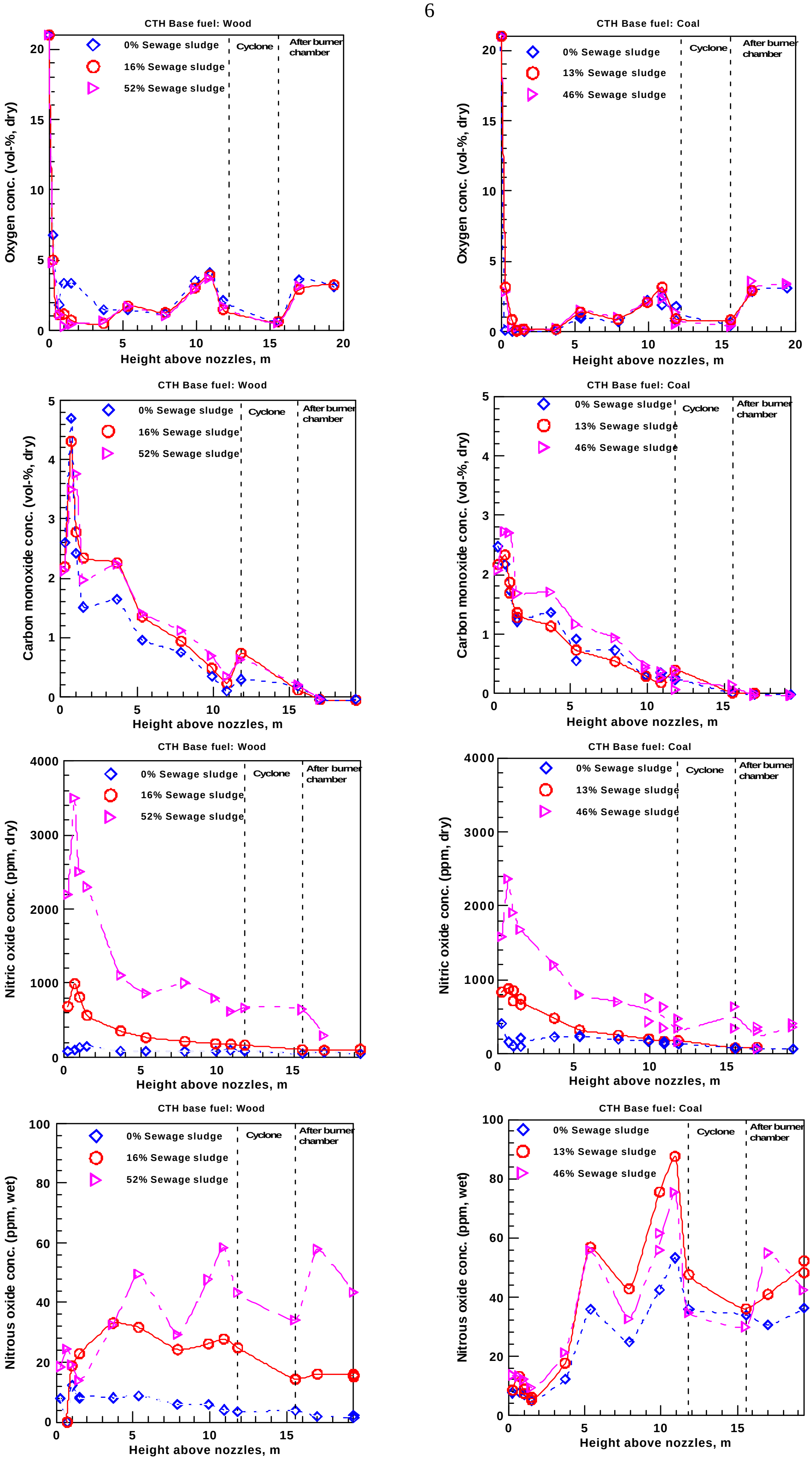

Fig. 4. Concentrations of O2, CO, NO, and N_2O on the centre-line of the CTH boiler during co-combustion of coal or wood with dried sewage sludge.Advanced staging.

disappear, at least for the pure fuels. There is a strong influence of the sludge with its high nitrogen content, and the NO concentration is extremely high in the locations where combustion takes place, in the bottom bed. As the gas moves upwards, NO is reduced and the concentrations falls. The concentration of N_2O is low. As measured several times before, the N_2O concentration increases on the way of the gas up in the combustion chamber, [4],[5]

Sewage sludge may contain considerable quantities of metals that can serve as catalysts for the gaseous emissions. For instance the present sludge contains 70 gram of iron per kg ash in the form of iron oxide or iron converted into oxide in the bed. This can be compared with the corresponding quantity of 7 g/kg ash for the coal used. The effect is 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 possible catalytic effect cannot be isolated in the co-combustion tests carried out, but catalytic effects can have been present. The catalytic effect has been identified in a special test, where iron oxide powder (Fe_3O_4 with an average size of 20 µm) was introduced into the cyclone of the CTH boiler during combustion of coal, Fig. 5. The figure shows the weight of the feed 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 sludge. The effect was seen as an immediate rise of the NO concentration from 100 ppm to 300 ppm. When the supply of iron oxide was stopped, the NO emission gradually returned to its original level as the iron disappeared. There are no data to relate this experience to the present sludge results, but the existence of catalytically active species in the sludge may affect the emission of nitrogen oxides especially.

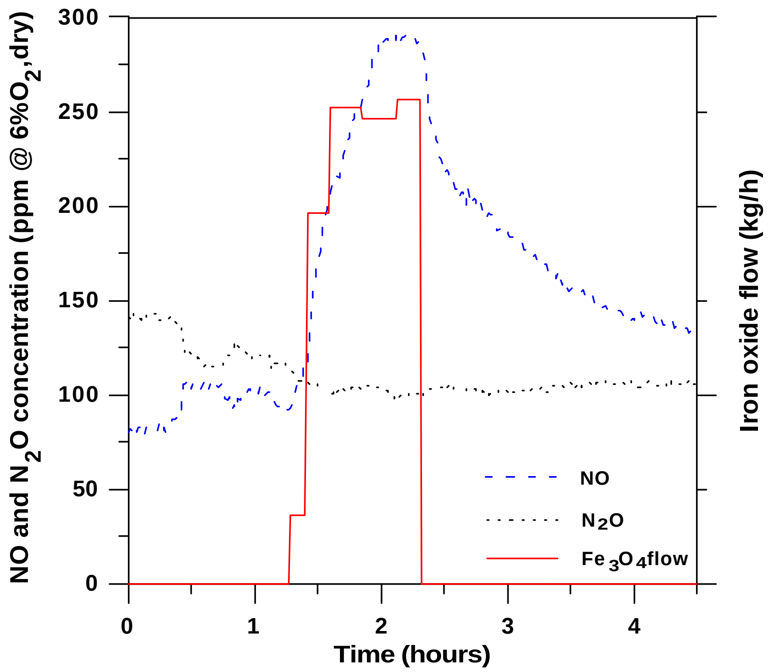

Fig. 5 Addition of iron oxide (Fe_3O_4) to the CTH combustion chamber during combustion of coal under normal operating conditions. Between t=1.42 and t=2.30 the average iron oxide addition is 485 kg/h which is equal to 2.8 kmol/h.

Conclusions

The emissions of NO and N_2O from co-combustion of sewage sludge in CFB with the base fuels wood or coal is characterized by the following:

Co-combustion of sludge both with coal or wood is feasible without excessive emissions of nitrogen oxides thanks to the strong reduction in the furnace. Conversion of the fuel nitrogen to nitrogen oxides is only a few percent.

The advanced staging method works well for coal combustion but has little significance when high volatile fuels such as wood and sludge dominate the combustion in the furnace.

NO emissions from wet sludge are similar or even lower than those from dried sludge. The reason is not clear but an effect of volatile fuel nitrogen compounds is suspected. This needs further investigations.

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