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Co-Combustion of Sewage Sludge with Wood/Coal in a Circulating Fluidised Bed Boiler- A Study of NO and N_2O Emissions

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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%), and the conversion of fuel nitrogen to NO or N_2O is only a few percent. However, air staging as such is not efficient for high volatile fuels, and any air supply method can be applied in such a case, in contrast to combustion of coal, when the air supply arrangement has a decisive influence.

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 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 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. Fluidised 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 on the emission performance? 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 and the results 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 air supply is staged in such a way that primary air is introduced under near-stoichiometric conditions and final air for completion of combustion is added in the particle-free space downstream of the cyclone in a circulating fluidised bed (CFB) combustor, Fig. 1. This 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.

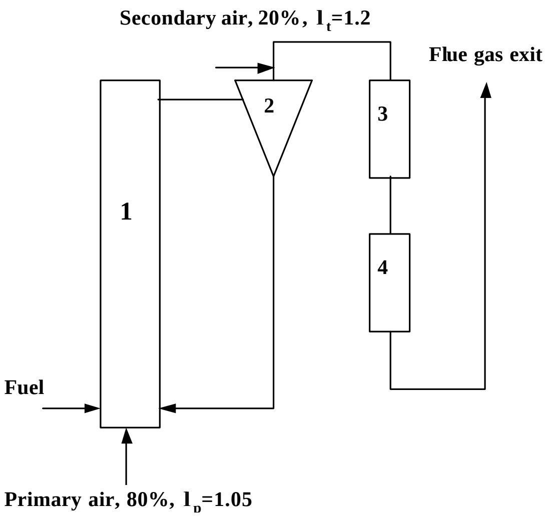

Fig. 1. CFB combustor showing “advanced” air staging. 1 Combustion chamber, 2 Particle separator, cyclone, 3 Afterburner, 4 Convection path.

Fuels and Experimental Equipment

Two combustors were used in the tests: the 12 MW CFB boiler at Chalmers University of Technology (CTH) [2] and a laboratory CFB at the Technical University of Hamburg-Harburg (TUHH) [1], Fig. 2. Both devices, although different in size, look in principle like the scheme shown in Fig. 1. The combustion chamber (1) of the Chalmers boiler has a square cross-section of about 2.25 m^2 and a height of 13.6 m. Fuel is fed on top of the bottom bed. 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 ^{o}C before cleaning in a secondary cyclone and a bag filter. The gas concentrations, the “emissions”, were measured by means of a comprehensive set of gas analysers, some of which take samples downstream of the filter and some serve for in-furnace measurements. The pilot scale unit of TUHH consists of a cylindrical combustion chamber with a diameter of 0.1 m (cross-section area of 0.008 m^2) and a total height of 15 m. Although this device is significantly smaller than the CTH boiler, it has been shown in previous investigations [4] that the emissions are practically the same as those from the CTH unit if suitable similarity rules are obeyed in the operation. The operation of the plant, as well as of the gas analysis system, in TUHH was similar to that of CTH, [1].

The operating conditions maintained during the tests were typical for CFB operation. Some data from the advanced staging tests are presented in Table 1. During other air supply measurements bed temperature, total excess air ratio and fluidisation velocities were maintained as close as possible to those of the table. For obvious reasons the fluidization velocities were slightly affected when the air supply was changed but this minor change in conditions has been shown in separate tests not to affect the emission results.

The same fuels were used in both plants, except for the wet sludges that originated from local sewage treatment plants. The two base fuels were bituminous coal and wood pellets. Sludge

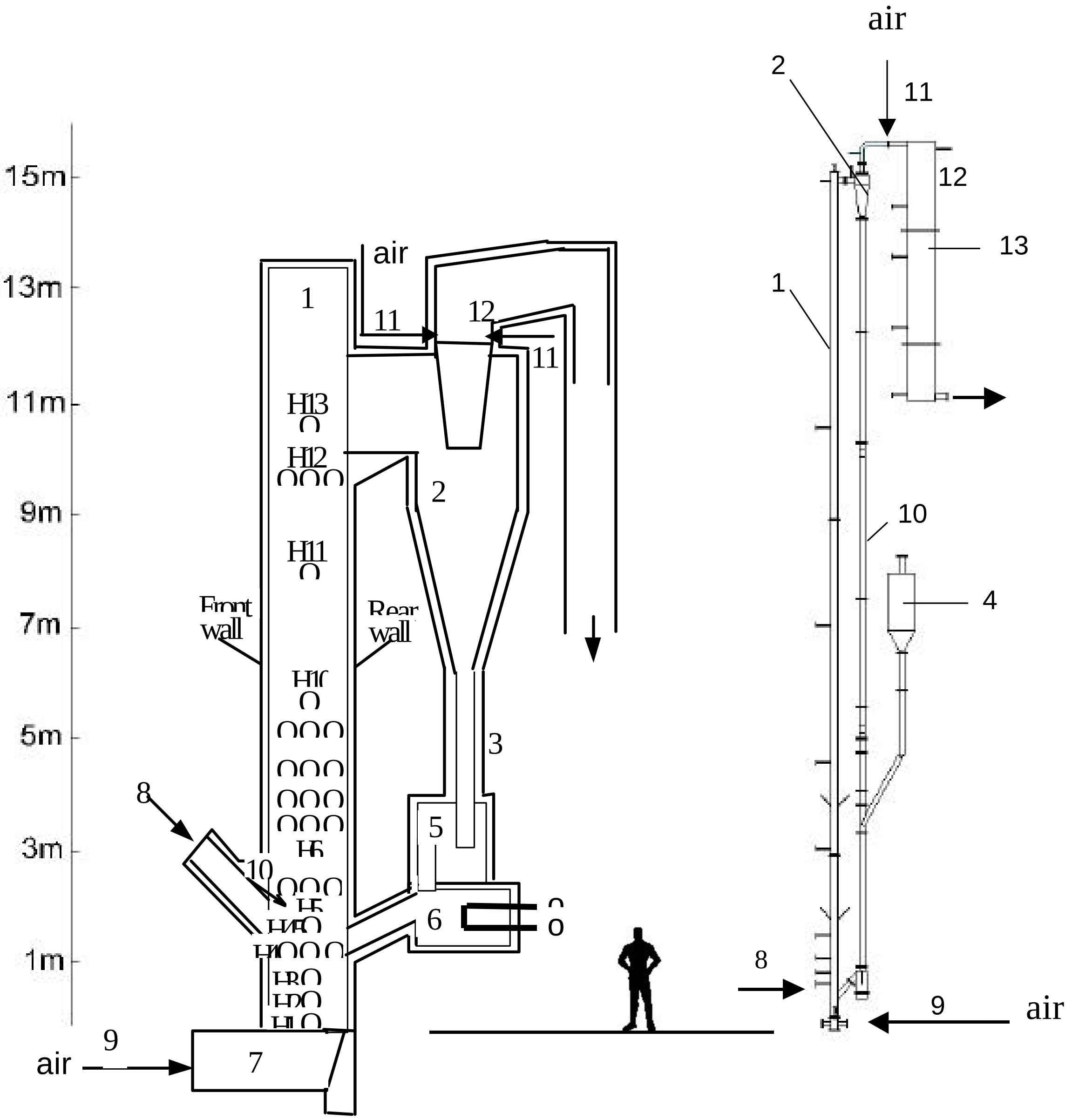

Fig. 2: The CFB test facilities at CTH in Göteborg (left) and at TUHH in Hamburg (right): (1) combustion chamber, (2) cyclone, (3) particle return line, (4) bed material hopper, (5) particle seal, (6) heat exchanger, (7) windbox, (8) fuel feed, (9) primary air supply, (10) air into the fuel feed chute, (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

was added in quantities up to 50% of the energy content of the mixture. The sludges were dried sewage sludge with an average moisture content of 19% and mechanically de-watered sewage sludge with a moisture content of 70%. The wet sludge could only be used in minor energy fractions, as is obvious from the composition of the fuels (the high water content), given in Table 1, because of the desire to run all tests under similar operation conditions, that is, at constant temperature as given in Table 2.

Table 1. Operating 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

Table 2. Fuel properties

	Bituminous coal	Wood pellets	Sewage sludge, dry	Sewage sludge, wet
Proximate analysis				
Water (wt-%, raw)	9	9	19	70
Ash (wt-%, dry)	17	0.8	38	52
Combustibles (wt-%, dry)	84	99	62	48
Volatiles (wt-%, daf)	35	81	91	94
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)*				
Hu, daf	32	19	21	20
Hu, raw	25	17	10	1.1

daf= dry and ash free, raw= as received

Results

A comparison of the emissions of NO and N_2O with coal and wood pellets as base fuels during co-combustion of dried sewage sludge is seen in Fig. 3. The data reflect the properties of the fuels and the conversion of fuel nitrogen to NO and N_2O. The conversion is only a few percent for coal but may amount to 10-20% for wood as observed before [4]. 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 to wood makes the emissions increase, but not much and only to the low level of coal. In general, the trends shown in Fig. 3 correspond to a decreasing conversion of fuel nitrogen to NO or N_2O with an increasing fraction of sludge. The figure also illustrates the similarities and differences in emissions from the two combustion units. In view of the large content of fuel nitrogen involved the differences between the two plants should be considered small.

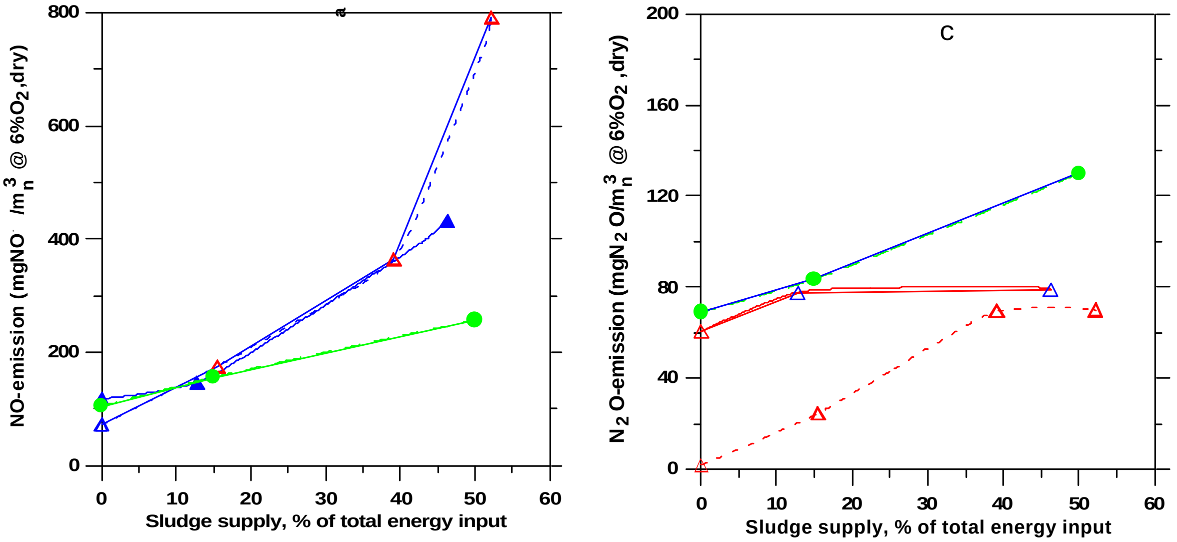

Fig. 3 Emissions of NO and N_2O during advanced air staging

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

● TUHH: Co-combustion of coal and sludge

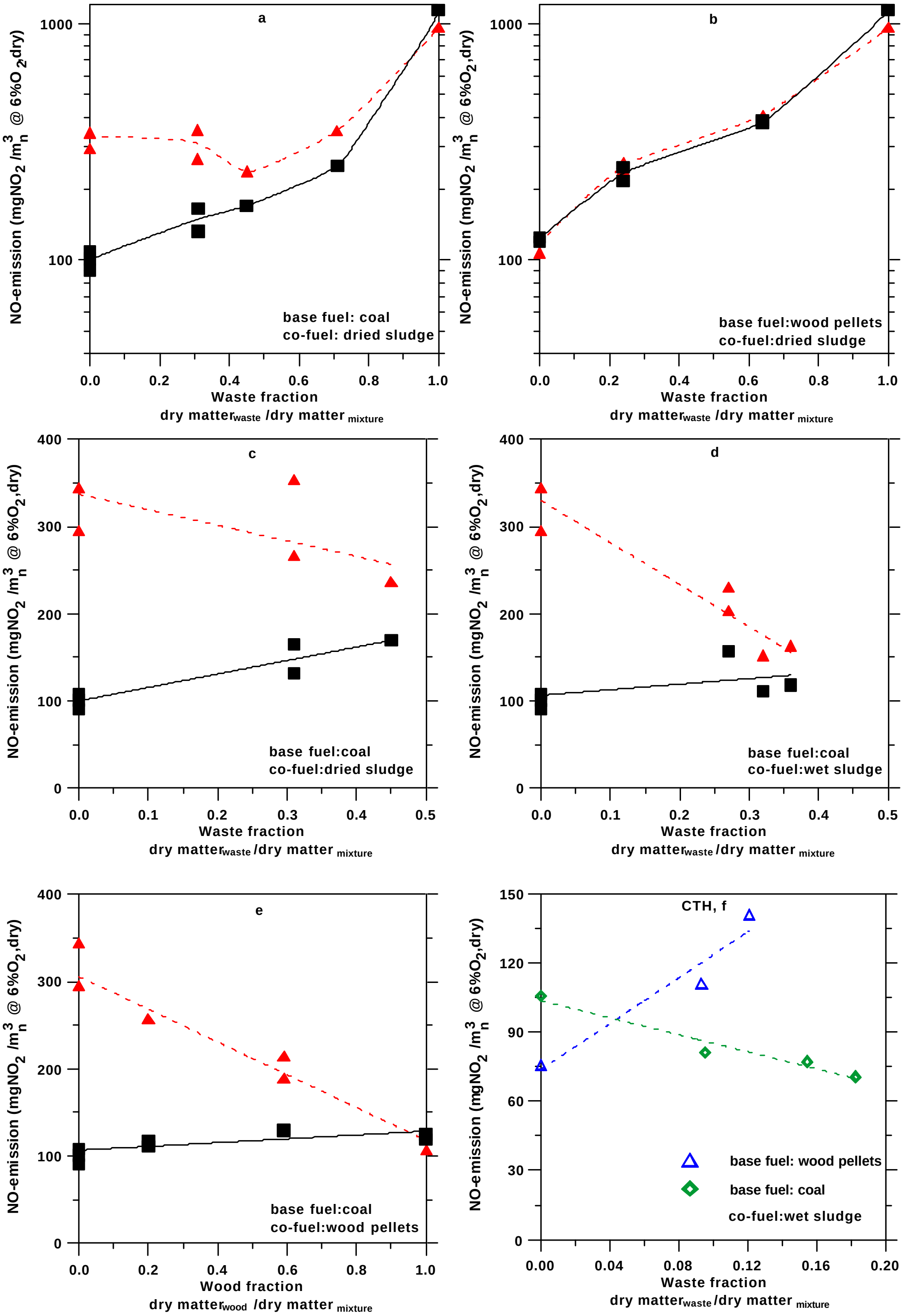

Fig. 4a-f. Influence of fuel and air staging. ♦ no-staging,■ advanced staging. Note that the horizontal scales sometimes differs and that logarithmic scales are used in some diagrams. Data are recorded on the CFB reactor at TUHH [1]. Figure 4f from data recorded in the CTH boiler

Figure 4a-e is based on data obtained in the combustor at TUHH. 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 4f, is for wet sewage sludge co-combusted with coal or wood in the Chalmers boiler.

The influence of staging is clearly seen from a comparison between no-staging and staging for the pure fuels (waste fraction=0); coal in Figs 4a,c,d and e, and wood in Fig 4b. Advanced staging gave a considerable reduction of the emission in the case of coal, but there is no difference between the air staging cases at all in the case of wood, Fig. 4b. The latter result was obtained again in the extreme case for 100% wood, Fig. 4e. Particularly in this diagram a gradual reduction of the influence of staging is found as the wood fraction increases, from a great difference between staging and no-staging when coal dominates the fuel mixture, to a small difference for high fractions of wood. The organisation of the air supply is more important for coal having a higher content of char than for wood. This conclusion holds also for sludge in Fig. 4a and in the extreme case of co-combustion of wood and sludge, both having a low content of char, in Fig 4b, where no influence at all of staging is seen. In fact, on the whole, the impact of air supply is rather small or negligible for high volatile fuels. The standard explanation [4] 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. Note the very high emission for pure sludge (Fig. 4a,b) and the reasonably low emission for wood (Fig. 4b,e). Wood is useful for the present comparison because of its low nitrogen content. A comparison between coal/dried sludge, Fig. 4a, coal/wood, Fig. 4e and wood/dried sludge, Fig. 4b, reveals that, in all cases when nitrogen is added in large quantities with the sludge, the NO emission increases. The decrease, or at least the very slight increase, in the case of coal/wood with increasing fractions of wood is a consequence of two opposite processes: reduction of the total fuel nitrogen added and simultaneously a lower reduction capacity as the char content in the bed decreases. However, this explanation does not hold for coal/wet sludge in Fig 4d that behaves like coal/wood in Fig 4e. 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. 4f 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. 4a (as well as in Fig.3). On the other hand, co-combustion of wood pellets with wet sludge (Fig. 4f) leads to an increase of the NO-emission, similar to the trend in Fig.3 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. (Note that the nitrogen content in the wet sludge is high but somewhat lower than that in the dried sludge. The similarity between the analysis results arises because the the analysis is made on dried matter. Some ammonia contained in the moisture has escaped.)

In Fig. 5 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 to a very low concentration 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 in the CTH combustor is most likely because of mixing effects, although the air was evenly supplied to the bottom air distributor with exception of

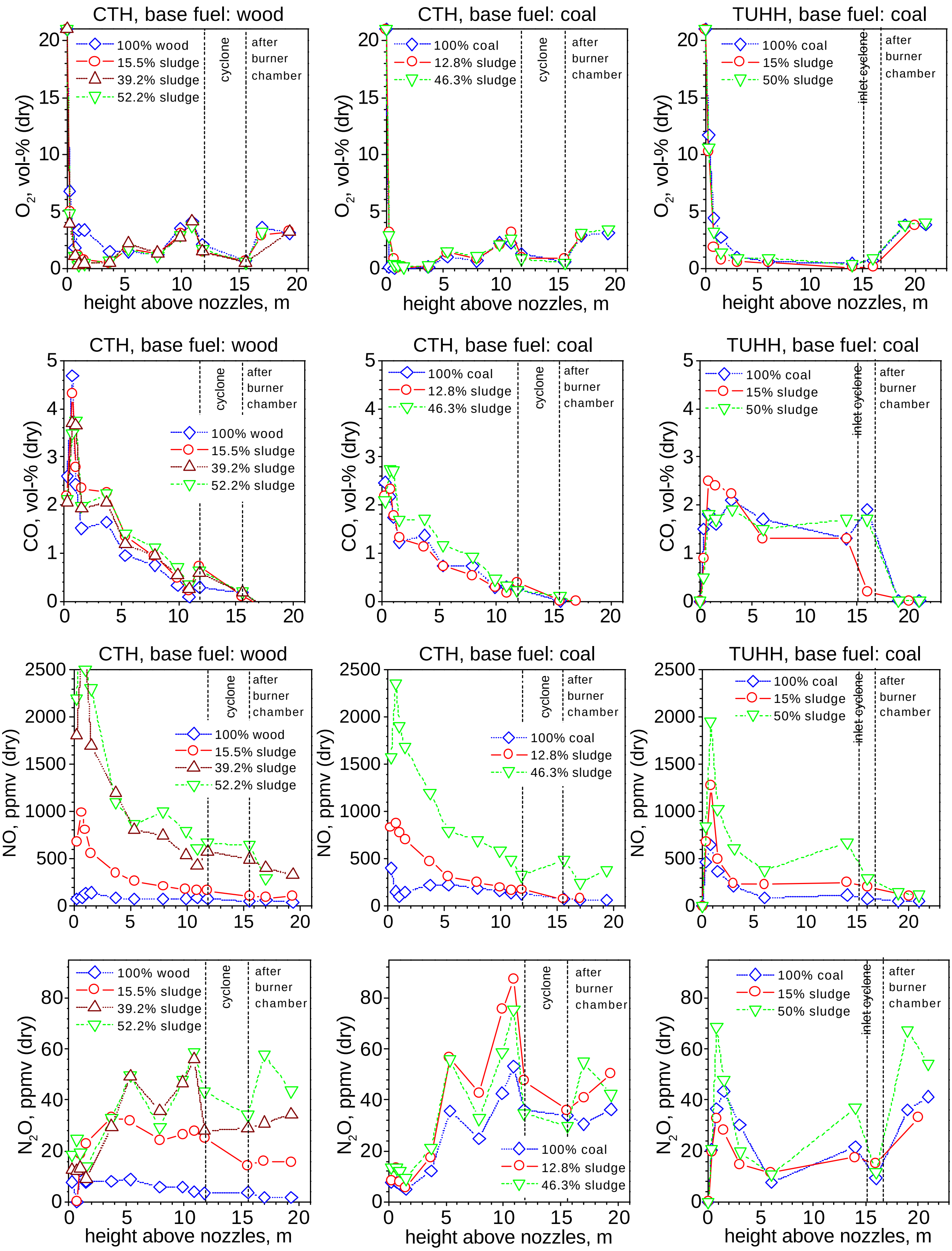

Fig. 5. Concentrations of O2, CO, NO, and N_2O on the centre-line of the combustion chamber of the CTH and TUHH test facility during co-combustion of coal or wood with dried sewage sludge. Advanced staging.

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 gives an indication of the progress of combustion, as well as of the release of volatiles. As expected, the data for wood are higher than those of coal. Also shown in Fig. 5 are the profiles of NO and N_2O. Note the differences in scale in the diagrams for NO and N_2O. The large scale for NO makes the exit concentrations disappear, at least for the pure fuels. In opposite to the oxygen profiles, 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 fall. 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, [3] [5]. However, in the TUHH unit there is a more complex behaviour, and surprisingly, a formation of N_2O in the afterburner downstream of the cyclone.

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: 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. 6. 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,

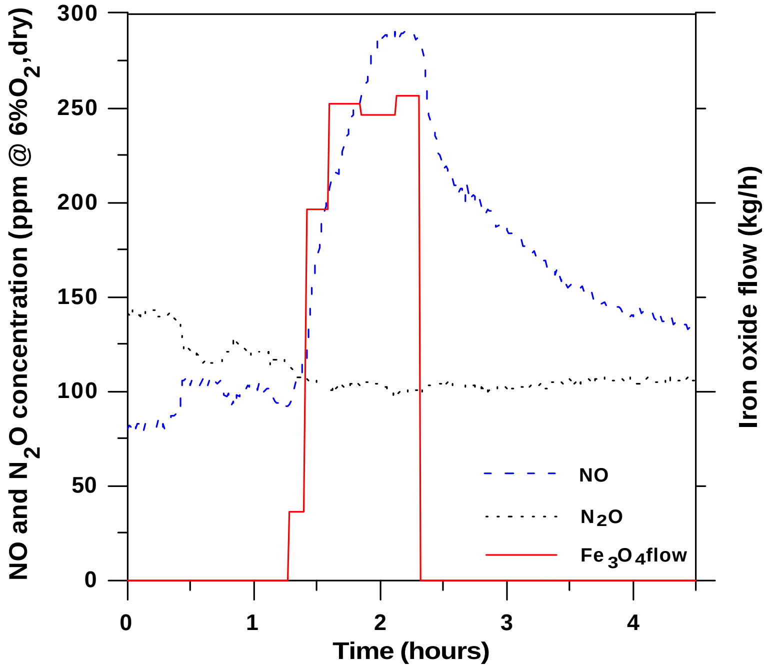

Fig. 6 Addition of iron oxide (Fe_3O_4) to the CTH combustion chamber during combustion of coal under normal operating conditions. Between t=1.42 and t=2.30 the average iron oxide addition is 485 kg/h which is equal to 2.8 kmol/h.

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.

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 taking place for both fuels. 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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