Solids Distribution and Gas Concentrations in the Furnace of a CFB Boiler during Co-Combustion of Bituminous Coal with Municipal Sewage Sludge

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Investigation of Solids Distribution and External Solids Flux in a Circulating Fluidized Bed Boiler

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List of papers

The thesis is based on the following papers:

I. Edvardsson, E., Åmand, L.-E., Thunman, H. and Leckner, B. (2006) "Solids Distribution and Gas Concentrations in the Furnace of a CFB Boiler during Co-Combustion of Bituminous Coal with Municipal Sewage Sludge", Department of Energy and Environment, Chalmers University of Technology.

II. Edvardsson, E., Åmand, L.-E., Thunman, H., Leckner, B. and Johnsson, F. (2006), "External Solids Flux Measurements in a CFB Boiler", Department of Energy and Environment, Chalmers University of Technology.

Other papers, not included in this thesis:

Summarizes part of the content of Paper I:

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Summarizes part of the content of Paper II:

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PAPER I

Solids Distribution and Gas Concentrations in the Furnace of a CFB Boiler during Co-Combustion of Bituminous Coal with Municipal Sewage Sludge

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Abstract

In this work, bituminous coal was co-fired with municipal sewage sludge in a 12 MW_{th} circulating fluidized bed (CFB) research boiler. The fraction of sewage sludge (both wet and dry) in the feed was varied in the range 0-67 % (on dry mass). The impact of co-combustion on ash leaving the boiler, bed material in the furnace and concentrations of O_2, CO_2, CO and total hydrocarbons throughout the furnace was studied. In order to evaluate the influence of the wide size distribution of the coal on the results, the coal was pre-sieved into a fine and a coarse size fraction and separately burned. The higher ash content in the sewage sludge resulted in increasing fly ash flows and lower combustible content in the fly ash with increasing fraction of sludge in the fuel mix. The bottom ash flow and combustible content were more sensitive to the feed coal size distribution than to the sludge supply. Compared to coal combustion, co-combustion of coal with sewage sludge was found to lead to a higher concentration of fine solids in the furnace, caused by attrition of sludge ash particles. Furthermore, as the density of sewage sludge ash is lower than that of coal ash, coarser sludge ash particles than coal ash particles could be entrained from the bottom bed. These two phenomena contributed to wider solids size distributions throughout the furnace in the case of co-combustion with sewage sludge. The effect of the entering coal size distribution on the size distribution of the inert ashes was negligible compared to the impact of the sludge fraction in the feed. The size distributions of the combustible solids in the bed material, on the other hand, were dependent on variations in feed size distribution of the coal rather than on sludge supply. The introduction of sewage sludge in the fuel mix resulted in greater measured concentrations of CO and total hydrocarbons in the furnace, leading to an increased combustion of volatiles above the bottom bed and higher temperatures in the top of the furnace.

Introduction

Production of sewage sludge from wastewater treatment plants is increasing at the same time as stringent requirements are imposed on traditional disposal methods, e.g. by the EU directive 99/31/EC on the landfill of waste [1]. Combustion of sewage sludge is gradually replacing methods such as landfilling, dumping and recycling in agriculture as a feasible and environmentally sustainable disposal pathway [2]. For instance, sewage sludge may be mono-incinerated or co-fired together with a fuel having a higher heating value such as bituminous coal. The latter option is suitable when the moisture content of the sludge is too high to sustain autothermal combustion, or if the rate of production of municipal sewage sludge in a region is limited. Co-combustion is most conveniently carried out in a fluidized bed boiler, thanks to the fuel flexibility of such a unit. Apart from disposing of the sewage sludge in an efficient way, the energy in the sludge can then be recovered. The climate effects due to carbon dioxide emissions from the boiler are also reduced when part of the coal is replaced by sludge. However, introducing sewage sludge into the fuel mix leads to altered conditions for combustion, fluid dynamics and heat transfer in a fluidized bed boiler due to the different properties of the fuels.

Bituminous coal contains about 5-20 % moisture, 5-10 % ash (on dry mass), 20-40 % volatiles (on dry and ash-free mass) and 60-80 % fixed carbon (on dry and ash-free mass). The composition of sewage sludge is quite different, with up to 80 wt% moisture, up to 50 wt% ash (on dry mass), over 90 wt% volatiles (on dry and ash-free mass) and less than 10 wt% fixed carbon (on dry and ash-free mass) [2]. Consequently, the overall combustion process in a fluidized bed is different for the two fuels. The heating of wet sewage sludge to furnace temperature leads to the release of a large amount of moisture, something that is often negligible for coal. As most of the combustibles in coal are present as fixed carbon, char combustion governs the coal combustion process. Combustion of sludge, on the other hand, is dominated by the release and combustion of volatiles, while char combustion plays a minor role. Besides the lower content of fixed carbon in sludge, sludge char appears to be more reactive than coal char [3]. Thus, the carbon loading in the bed is low for sewage sludge combustion as compared to coal combustion [4]. The ash characteristics are different for coal and sewage sludge [3]. Coal ash exists as incoherent inclusions of ash material in a coherent carbon matrix. As a result, the interaction of the attrition and combustion processes is strong. Combustion of a sewage sludge particle, on the other hand, leaves a coherent ash skeleton after char burnout.

The physical quality of sewage sludge varies with the moisture content [2]. Wet sludge flows easily, while sludge with moisture content around 40-70 % is sticky and unable to flow. Dry sludge (with moisture content <35-40 %) has a granular character and mixes without difficulty. Dry sludge may be mono-incinerated, but if carried out in a separate device, the drying process requires energy and generates by-products that must be taken care of, such as condensate, gaseous CO and dust. It may also be difficult to store and handle due to its dusty nature, which introduces the risk of self-ignition. Wet sludge cannot sustain autothermal combustion, and can only be burned if mixed with a fuel with a higher heating value.

In this work, bituminous coal was co-fired with municipal sewage sludge in a circulating fluidized bed (CFB) boiler. The influence of co-combustion on ash leaving the boiler, bed material in the furnace and gas concentrations of O_2, CO_2, CO and total hydrocarbons in the furnace was studied.

Experimental background

Bituminous coal was co-fired with different amounts of municipal sewage sludge using silica sand as make-up bed material. Both wet and dry sludge were used. In addition, a batch of the coal was pre-sieved into two different size fractions that were separately burned.

Boiler

The tests were conducted in the 12 MW_{th} CFB boiler at Chalmers University of Technology, schematically shown in Fig. 1.

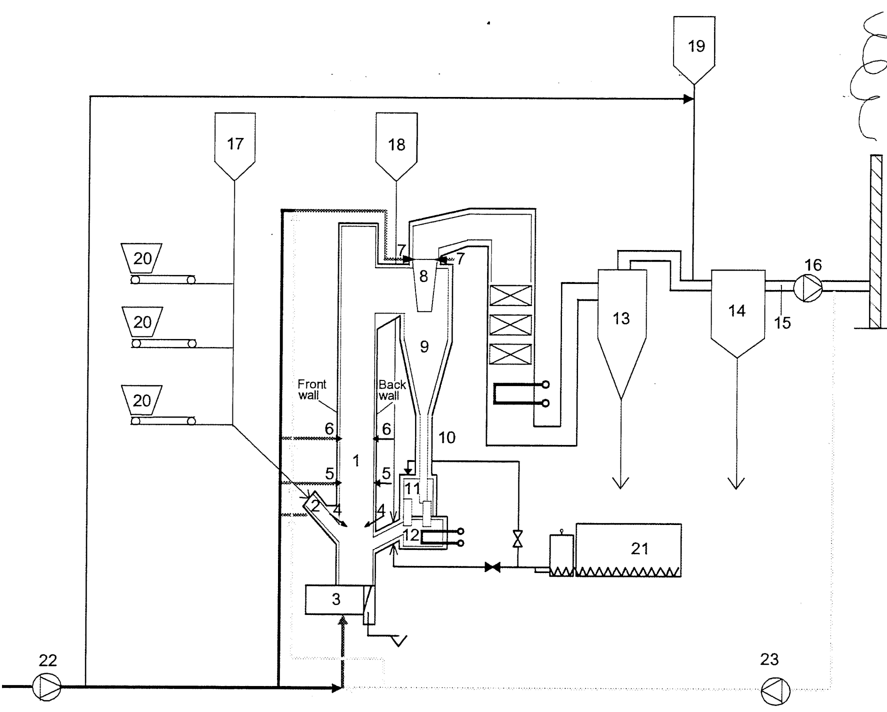


Figure 1 The 12 MW_{th} CFB boiler at Chalmers University of Technology with (1) furnace, (2) fuel feed chute, (3) air plenum, (4) secondary air inlet at 2.1m, (5) secondary air inlet at 3.7m, (6) secondary air inlet at 5.4m, (7) secondary air inlet into cyclone exit duct, (8) cyclone exit duct, (9) primary cyclone, (10) cyclone return leg, (11) loop seal, (12) external heat exchanger, (13) secondary cyclone, (14) bag filter, (15) gas extraction probe for emission monitoring, (16) flue gas fan, (17) sand bin, (18) lime bin, (19) hydrated lime bin, (20) fuel bunkers, (21) sludge pump, (22) air fan and (23) flue gas recirculation fan.

The furnace (1) has a square cross-section of 2.2 m^2 and a height of 13.6 m. Fuel (including dry sludge) and make-up bed material are fed to the bottom of the furnace through a fuel chute (2). Wet sludge is fed to the return pipe using a piston pump (21). Separation of the circulating solids and the flue gas takes place in the primary cyclone (9). The circulating solids are then transported through the cyclone return leg (10) to the loop seal (11) and the external heat exchanger (12) before returning to the furnace. Primary air is supplied to the air plenum (3) and enters the bottom of the furnace through the air distributor. Secondary air can be injected at different heights in the furnace (4, 5, 6) or downstream of the primary cyclone (7). The flue gas passes through the exit duct of the cyclone (8) and continues through the convection path. The fly ash is separated from the flue gas in a secondary cyclone (13) and a bag filter (14).

Fuels and make-up bed material

The base fuel used for the co-combustion tests was a commercial Polish bituminous coal from the Katowice district (referred to as "Polish coal III" in [5]). The sewage sludge used as secondary fuel was from the wastewater treatment plant Himmerfjärdsverket, located outside the city of Södertälje, Sweden. The wastewater treatment included digesting and precipitation with ferrous iron (Fe^{2+}) for phosphorus removal. The composition of the produced sewage sludge was representative of sludge treated in this way [6]. The water content of the sludge was reduced in two different ways: mechanical dewatering and pre-drying. The sludge was either mechanically dewatered (wet sludge) or mechanically dewatered and subsequently pre-dried (dry sludge). The properties of the fuels are given in Table 1. The uncertainties were calculated as three times the standard deviation of the analyzed samples. Silica sand was used as make-up bed material.

The fuels and the sand were sieved to determine the size distribution of the material entering the boiler. The coal had a wide size distribution, which also varied significantly between the test days. Before transport to the boiler, the coal shipment was crushed and stored in large piles. Size fractionation occurred during storage and handling, leading to variations in the size distribution of different loads delivered from the storage facility to the boiler (similar problems related to fuel quality may very well arise for combustion in full-scale boilers). In order to evaluate the importance of the variations in the size distribution of the coal, a batch of coal was sieved into a coarse and a fine size fraction, which were then separately burned. The dry sewage sludge had a narrower size distribution that was relatively constant throughout the test period. It was not possible to sieve the wet sludge due to its high moisture content. The average cumulative size distributions of coal (both the wide size distributions used initially and the pre-sieved coal fractions), dry sewage sludge and sand are shown in Figure 2. Shaded areas represent the distributions of the initial coal, the coarse coal fraction and the dry sewage sludge (despite the coarse fraction being sieved, the variation in distribution between three test days was relatively large compared to the fine coal fraction, the dry sewage sludge and the sand). Mean particle diameters of the coal, dry sewage sludge and sand are shown in Table 2.

Table 1 Fuel properties [1]

	Bituminous coal	Sewage sludge, dry	Sewage sludge, wet
Proximate analysis (wt%)			
Moisture (raw)	10 ± 3	22 ± 14	79 ± 2
Ash (db)	6 ± 1	36 ± 1	37 ± 1
Combustibles (db)	93 ± 4	65 ± 11	62 ± 7
Volatiles (daf)	34 ± 2	89 ± 4	93 ± 7
Ultimate analysis (wt%, daf)			
C	81.3 ± 1.1	52.2 ± 1.1	52.1 ± 0.0
H	4.9 ± 0.0	7.4 ± 0.0	7.5 ± 0.2
O	11.7 ± 1.3	31.0 ± 0.5	31.0 ± 0.3
S	0.4 ± 0.0	2.3 ± 0.1	2.3 ± 0.1
N	1.6 ± 0.2	7.2 ± 0.6	7.1 ± 0.0
Cl	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Lower heating value (MJ/kg)			
H_u (raw)	26.6 ± 0.9	9.6 ± 1.5	0.8 ± 0.1
H_u (db)	30.0 ± 0.7	13.4 ± 0.1	13.3 ± 0.5
H_u (daf)	31.9 ± 1.1	21.0 ± 0.1	21.2 ± 1.2

[1] raw = as received, db = dry basis, daf = dry ash-free

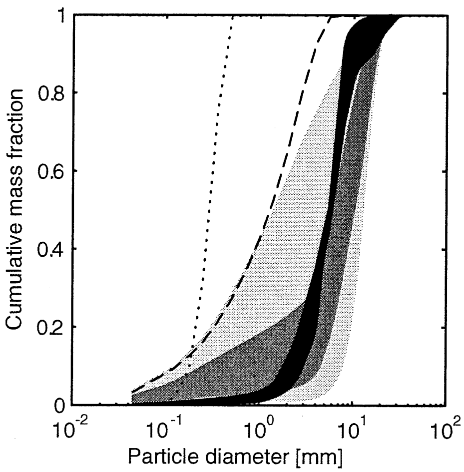


Figure 2 Cumulative size distributions of sand (dotted line), coal of wide size range (light grey shaded area), coarse coal (dark grey shaded area), fine coal (dashed line), and dry sewage sludge (black shaded area)

Table 2 Mean particle diameters of coal, dry sewage sludge and sand

	Coal (wide size distribution)	Fine coal fraction	Coarse coal fraction	Dry sewage sludge	Silica sand
Mass mean diameter (mm)	6.30	1.67	8.50	6.46	0.30
Sauter (surface) mean diameter (mm)	0.50	0.29	0.78	3.03	0.27

Table 3 Operating conditions

Test	A1	A2	A3	A4	A5	B1	B2
Fuel	Coal	Coal and 12 % wet sludge	Coal and 23 % wet sludge	Coal and 27 % dry sludge	Coal and 67 % dry sludge	Coarse coal	Fine coal
Number of days	11	2	4	4	3	5	3
Fraction of energy from sludge (%)	0	2 ± 1	4 ± 5	14 ± 6	47 ± 6	0	0
Dry mass fraction from sludge (%)	0	12 ± 2	23 ± 3	27 ± 4	67 ± 4	0	0
Thermal load (MW)	6.5 ± 0.2	6.2 ± 0.4	5.9 ± 0.2	6.4 ± 0.2	6.2 ± 0.3	5.7 ± 0.4	5.5 ± 0.5
Primary air/total air (%)	55.1 ± 0.6	55.9 ± 1.1	55.5 ± 1.1	56.4 ± 0.9	55.9 ± 2.1	46.1 ± 0.3	47.2 ± 0.6
Excess air ratio	1.21 ± 0.02	1.23 ± 0.01	1.23 ± 0.03	1.22 ± 0.01	1.22 ± 0.04	1.21 ± 0.01	1.21 ± 0.01
T_b (°C)	850 ± 1	849 ± 2	851 ± 2	850 ± 1	850 ± 4	850 ± 2	850 ± 2
T_{top} (°C)	865 ± 2	864 ± 5	877 ± 4	875 ± 3	876 ± 9	815 ± 3	820 ± 3
Δp (kPa)	6.4 ± 0.1	6.4 ± 0.2	6.3 ± 0.1	6.5 ± 0.2	6.8 ± 0.3	6.3 ± 0.1	6.3 ± 0.1
u_0 (m/s)	2.9 ± 0.1	2.6 ± 0.1	2.4 ± 0.1	2.6 ± 0.1	2.4 ± 0.1	2.8 ± 0.1	2.7 ± 0.1
$u_{0, top}$ (m/s)	5.1 ± 0.3	5.0 ± 0.5	5.0 ± 0.2	4.9 ± 0.3	4.9 ± 0.1	4.6 ± 0.1	4.3 ± 0.1

Experimental procedure

The operating conditions used in this work are shown in Table 3, where the number of test days for each test is also shown. T_b is the temperature in the bottom bed, T_{top} is the temperature in the top of the furnace, Δp is the pressure drop over the furnace, u_0 is the superficial velocity in the furnace below the secondary air inlet (based on the measured flow of primary air and flue gas recirculation) and $u_{0, top}$ is the superficial velocity in the top of the furnace (based on the flue gas flow). The uncertainties were calculated as three times the standard deviation of the data collected by the data acquisition system of the boiler (the data are mean values for one minute, with a sampling once every ten seconds).

Co-combustion tests (series A), including a reference case with pure coal combustion, were carried out in the year 2002. Additional tests with pre-sieved fine and coarse coal fractions (series B) were performed in the year 2003. In the latter tests, the thermal load was somewhat lower than for series A, and the air staging was slightly different, with lower fraction of primary air/total air. This led to a lower temperature in the top of the boiler as compared to test A1, as lower amounts of fine char were carried by the gas flow towards the top of the furnace to burn there. In addition, the higher fraction of secondary air cooled the combustion gases to a larger extent before they reached the top of the furnace.

The operating conditions were relatively stable during the test series. The control system of the boiler keeps the air flow constant for a set thermal load, with the fuel flow controlled by the oxygen concentration in the stack [7]. As the fraction of sewage sludge in the fuel fed to the boiler was increased, the moisture, volatiles and ash content of the fuel mix increased and the char content decreased. Increased moisture content leads to a lower combustion temperature. In order to maintain a constant bottom bed temperature as the sludge supply was increased, the amount of heat collected by the external heat exchanger and the flue gas recirculation were reduced. As a consequence, the total gas flow through the furnace varied somewhat between the tests, but the principal parameters, excess-air ratio and bottom bed temperature, were constant. Secondary air was injected at 2.1 m above the primary air distributor. In order to eliminate the interference of lime attrition on the behaviour of char and ash particles, no lime for sulphur capture was added to the bed.

Extensive measurements involving both gas and solids sampling and analysis were carried out. In addition, information was gathered from the data acquisition system of the research boiler. The system logs parameters such as temperatures, flows of gas and water and differential pressures measured in different parts of the boiler. Emissions measured in the stack and the weights of fuel, sand and ash containers are logged as well.

Solids were sampled on the centreline of the furnace at three heights (0.56, 3.7 and 7.9 m above the primary air distributor), indicated in Fig. 3. At 0.56 m (just above the bottom bed), samples were taken using an uncooled solids extraction probe. The samples were kept under reducing conditions (in a closed container) until they had cooled down. At 3.7 and 7.9 m of height (in the transport zone of the furnace, where the solids concentration is on the order of 1 kg/m^3), samples were taken using a solids extraction probe equipped with a cyclone and a container for collection of the particles, shown in Fig. 4. The probe, cyclone and container were all water-cooled. Solid samples were also extracted in the return leg of the cyclone, but due to the swirling flow of solids, propagating down from the cyclone, these samples were not found to be representative of the circulating bed material. Size analysis of the collected solid samples was carried out by sieving, using mesh sizes ranging from 0.045 to 50 mm. Proximate analysis was performed on each size fraction using a MAC 400 Proximate Analyzer. Samples of secondary cyclone and bag filter fly ash were also subjected to proximate analysis.

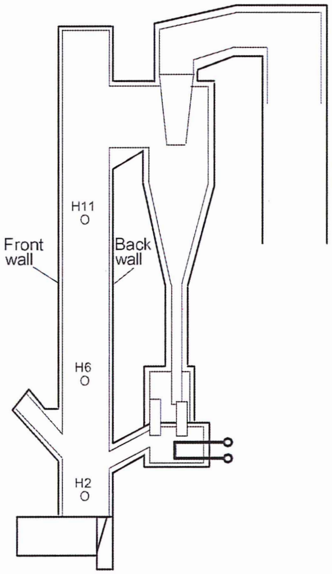
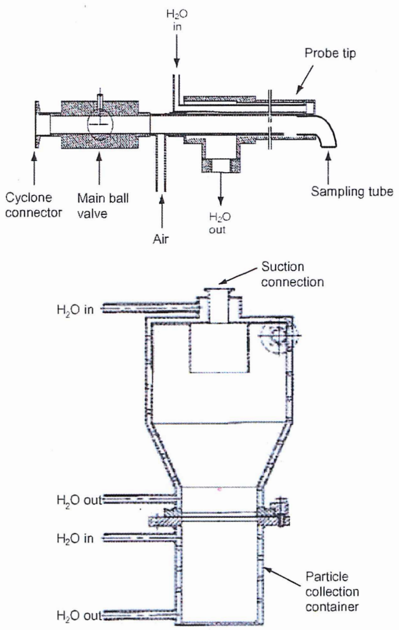


Figure 3 Positions used for solids sampling on the centreline



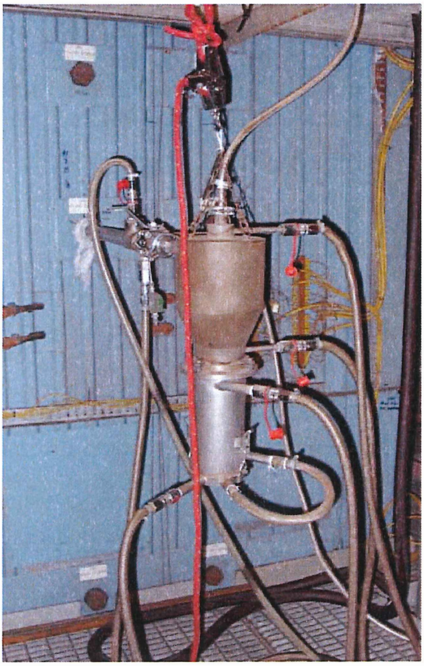


Figure 4 Shematic drawing of water-cooled particle extraction probe with cyclone and container (left) and photograph of the solids extraction equipment during the tests (right).

The solid samples extracted at 0.56 m were assumed to be representative of the bottom ash leaving the boiler (the bottom bed height was about 0.3 m during all tests, according to differential pressure measurements along the furnace height). In order to investigate the validity of this assumption, solids taken from the furnace at 0.56 m were compared to solids taken from the bottom ash container during the test with fine coal.

Before the start of the experimental program, the bed material in the boiler consisted of fresh sand. After the start of the series, the tests followed one after the other (the operating conditions were changed starting from the bed material resulting from the previous test). Solid samples were taken after 6 to 62 hours of stable operation, when the test was expected to have run for the number of hours required to reach steady state operation in terms of the particle size distributions. The boiler with entering and leaving solid flows is schematically drawn in Fig. 5.

The minimum time needed to attain steady state for the particle phase for a set of specified operating conditions is the time required for regeneration of the initial bed material. The mean solids residence time was calculated as $t_m = W/F_{tot}$, where W is the mass of material in the boiler, in kg, and F_{tot} is the total ash flow leaving the boiler ($F_{tot} = F_{fly\ ash} + F_{bottom\ ash}$), in kg/h. The total mass of bed material was taken as the sum of the mass of material in the furnace, as estimated from pressure drop measurements, and the mass of material in the return loop, estimated based on a case when the boiler was emptied of bed material as the pressure drop over the furnace was monitored. W was about 2600 kg for the chosen operating conditions. However, this method of calculating the residence time does not take into account the size segregation of the ash in the boiler. For virtually all the sand and the coarser ash, the flow of bottom ash is limiting for the residence time, as particles with sizes d_p>0.125 mm do not exit with the fly ash (based on particle size distributions of fly ash reported for co-combustion of wood and sewage sludge in the same boiler [8]). Assuming that the initial bed material consisted of sand or ash particles large enough to be separated by the cyclone, the mean residence time should instead be calculated as $t_m = W/F_{bottom\ ash}$. This resulted in residence times of 25-221 hours.

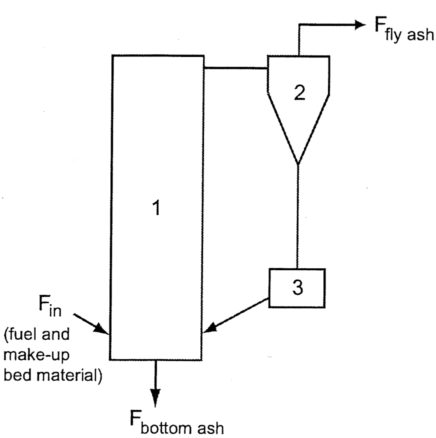


Figure 5 Solid flows entering (F_{in}) and leaving ($F_{fly\ ash}$ and $F_{bottom\ ash}$) the CFB boiler; (1) furnace, (2) cyclone and (3) loop seal and external heat exchanger.

Table 4 Fraction of initial bed material present in the boiler at times of solids sampling

	Coal	Coal and 12 % sludge	Coal and 23 % sludge	Coal and 27 % sludge	Coal and 67 % sludge	Coarse coal	Fine coal
Height above primary air distributor (m)	Fraction of initial bed material left in boiler, $\exp(-t_s/t_m)$ (%)						
0.56	77	95	94	87	65	16	81
3.7	95	97	96	91	82	86	80
7.9	96	96	95	90	78	84	92

To obtain a rough estimate of the fraction of initial bed material present in the boiler after a given period of time, the boiler was assumed to operate as a perfectly stirred tank reactor. The fraction of initial bed material still present in the boiler at the time of extraction of a solid sample, t_s, was calculated as $\exp(-t_s/t_m)$. The results of the calculations are shown in Table 4. It is clear that steady state for the particle phase was far from reached except at one sampling occasion during coarse coal combustion. In addition, the residence time in the boiler is longer for the circulating solids than for the non-circulating coarse material.

Gas concentrations of O_2, CO_2, CO and total hydrocarbons were measured on the centreline along the height of the furnace, and in cross-sectional planes (9 points in each plane) at four heights (0.67, 3.7, 5.35 and 9.9 m above the primary air distributor) during the co-combustion tests (series A). The gas sampling was performed using the probe described by Åmand et al. [9]. The positions used for gas extraction are shown in Fig. 6.

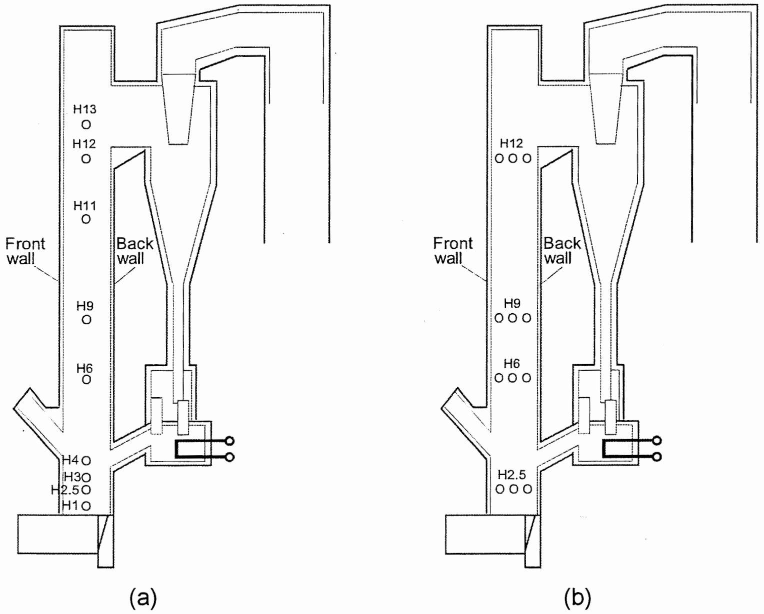


Figure 6 Positions used for gas sampling on centreline (a) and in cross-sectional planes (b)

Results

The obtained results illustrate the impact of co-combustion on ashes, bed material, and gas concentrations in the furnace. Firstly, the closure of the ash balances is evaluated in order to assess the uncertainty related to the results. Secondly, flows and combustible content of bottom ash, secondary cyclone ash and bag filter ash are compared for co-combustion of coal and sewage sludge and combustion of coal with varying fuel size distribution. Furthermore, the occurrence of increased attrition with higher fractions of sewage sludge in the fuel mix is investigated. This is done by comparing size distributions of solids extracted from the furnace during co-combustion of coal with a high fraction of sewage sludge with the expected size distributions in the case of no ash attrition. In addition, the size segregation between bottom bed material and the solids entrained by the fluidizing gas as well as the contribution of sand to the size distributions are illustrated. The widening of the size distributions with increasing fraction of sewage sludge in the feed is also shown. Finally, axial furnace concentration profiles as well as cross-sectional plane concentrations of O_2, CO_2, CO and total hydrocarbons are compared for combustion of coal and co-combustion of coal with sewage sludge.

Ash flows

As shown in Table 5, the closure of the ash balance was relatively good in all tests except for some of the days during combustion of coarse coal. The data are mean values calculated from results from the separate test days for each case, and the uncertainties are calculated as three times the standard deviation of the mean.

The fly ash flow leaving the boiler increased with increasing sludge supply, as seen in Fig. 7 (the flow of sand is included for comparison). This is consistent with the higher ash content of sewage sludge compared to coal. As more sludge is fed to the boiler, larger amounts of ash are present, and lower amounts of sand are required for regeneration of the fluidized bed. The secondary cyclone ash flow clearly increased with increasing sludge fraction in the feed. The bag house filter ash flow seems to increase with increasing sludge supply as well, but the effect was less dramatic than that of the secondary cyclone ash. The bottom ash flow was not significantly affected by a higher sludge supply; the slight visible increase was within the limits of variation in bottom ash flow for the tests with different coal size distributions (shown in Fig. 8). A reason for the variation in bottom ash flow may be that this parameter was used to control the pressure drop over the furnace. The combustible content in both secondary cyclone and bag filter ash decreased with increasing sludge supply, as shown in Fig. 9. The impact of the variation of the coal size distribution on the combustible content of the ash is illustrated in Fig. 10. The effect of co-combustion on the combustible content in the bottom ash was unclear, as the variation was comparable to that between the coal tests. In conclusion, co-combustion of coal with sewage sludge leads to higher fly ash flows and lower combustible content in the fly ash. The bottom ash flow and combustible content appear to be dominated by the coal size distribution entering the furnace rather than by the fraction of sludge in the feed.

Table 5 Closure of ash balance

	Coal	Coal and 12 % sludge	Coal and 23 % sludge	Coal and 27 % sludge	Coal and 67 % sludge	Coarse coal	Fine coal
Ash recovery fraction (out/in, %)	104 ± 16	96[1] (94-98)	108 ± 16	91 ± 16	87 ± 7	142 ± 67	80 ± 6

[1] Only 2 values included, no standard deviation available

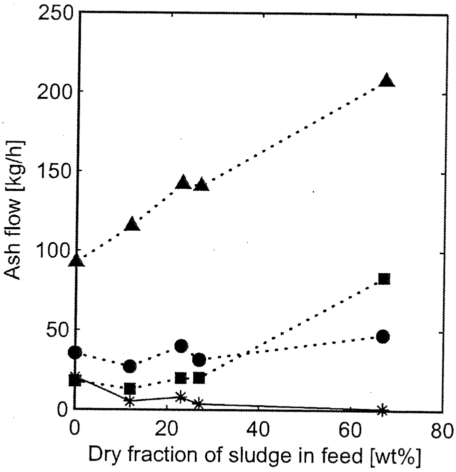


Figure 7 Flows of bottom ash (squares), secondary cyclone ash (triangles) and bag filter ash (circles) leaving the boiler vs. fraction of sludge in feed. Solid line with asterisks is sand flow entering the boiler.

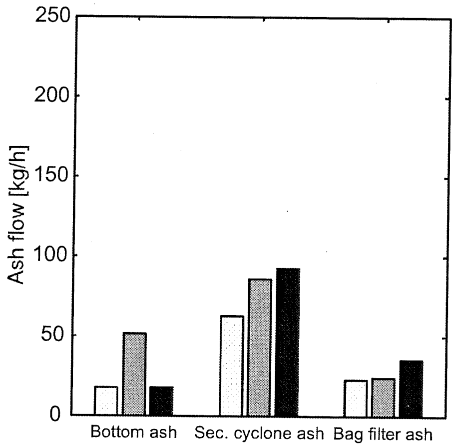


Figure 8 Flows of bottom ash, secondary cyclone ash and bag filter ash leaving the boiler during tests with fine coal (light grey), coarse coal (dark grey) and wide size distribution coal (black).

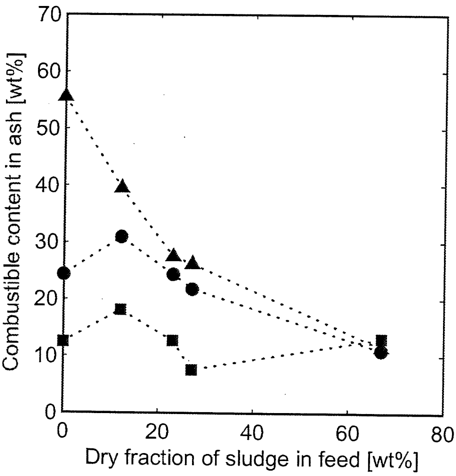


Figure 9 Combustible content in bottom ash (squares), sec. cyclone ash (triangles) and bag filter ash (circles) leaving the boiler vs. fraction of sludge in feed.

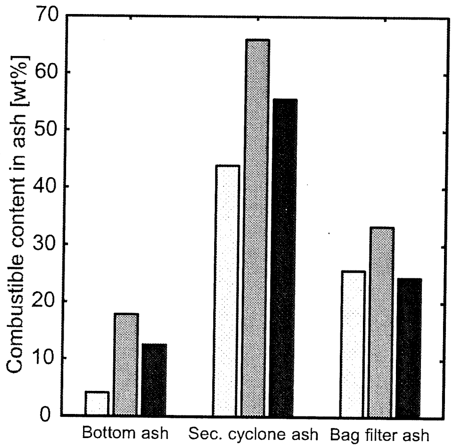


Figure 10 Combustible content in bottom ash, secondary cyclone ash and bag filter ash during tests with fine coal (light grey), coarse coal (dark grey) and wide size distribution coal (black).

Solid samples

Fig. 11 shows photographs of material extracted at 0.56 m during coal combustion, co-combustion of coal with 67 % sewage sludge, and combustion of wood pellets. The latter is included for comparison, as wood pellet combustion generates a minimum of ash, and the bed thus consists exclusively of sand. Large coal (black) and sludge (orange) particles are clearly visible in the material from the co-combustion case. Ferric oxide (Fe_2O_3) in the sewage sludge colours the bed material red.

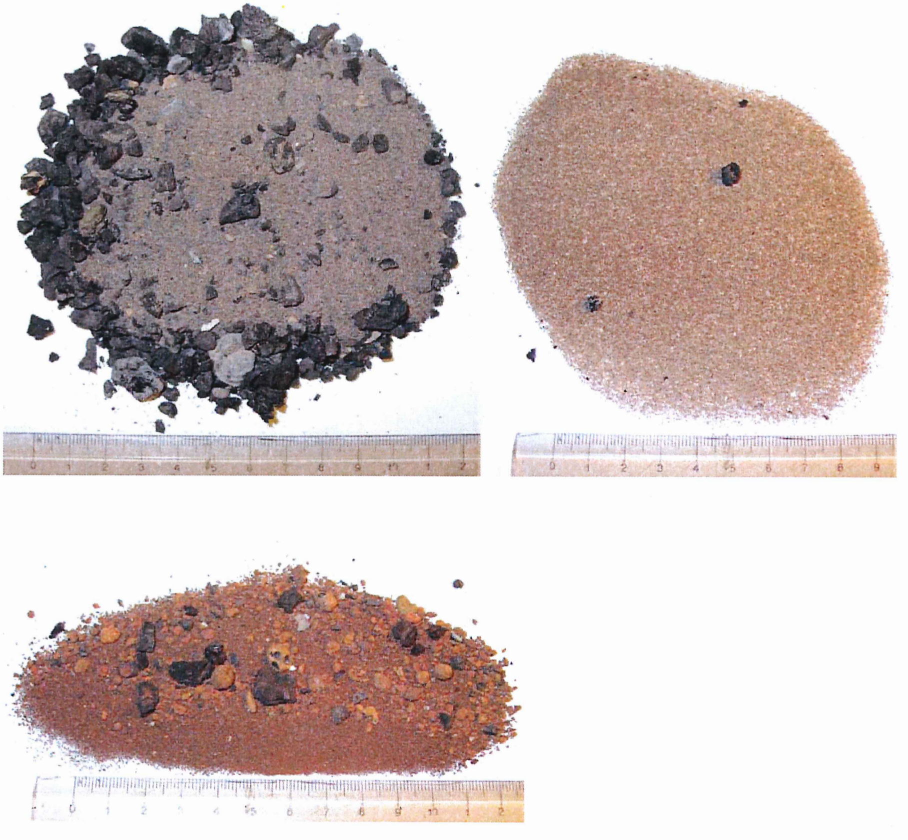


Figure 11 Bed material extracted at 0.56 m during coal combustion (upper left), co-combustion of coal with 67 % sewage sludge (lower left), and combustion of wood pellets (right). Scales in cm.

Fig. 12 compares the size distributions of samples taken in the splash zone (at 0.56 m) with the bottom ash for the test with fine coal. The size distribution of the samples from the splash zone describes the bottom ash fairly well, despite the difficulties associated with taking representative solid samples from a pile of material (such as in the bottom ash container).

The particle size distribution of the bottom bed material (extracted at 0.56 m) for co-combustion of coal with 67 % dry sewage sludge (test A5) is shown in Fig. 13. The result is compared with data from tests performed at the Technical University of Hamburg-Harburg (TUHH) within the EU project 7220-PR-124 [10]. In these tests, the same coal and sewage sludge as used in this work were burned in a pilot scale CFB unit described by Klett et al. [12]. The TUHH pilot scale combustor has been shown to yield emissions comparable to the CTH boiler, provided it is operated according to suitable similarity rules [13]. About 50 % each of coal and dry sewage sludge (on dry mass) were fed to the combustor, with sand as make-up bed material. The superficial gas velocity in the top of the riser was 4.2 m/s and the excess air ratio for combustion was 1.23, and solids sampling was performed in the bottom drain after four hours of operation. As seen in Fig. 13, the shapes of the cumulative particle size distributions of the bottom ash were similar for the two units. In this work, about 92 % of the total ash fed was sludge ash, whereas in the TUHH tests, about 86 % was sludge ash.

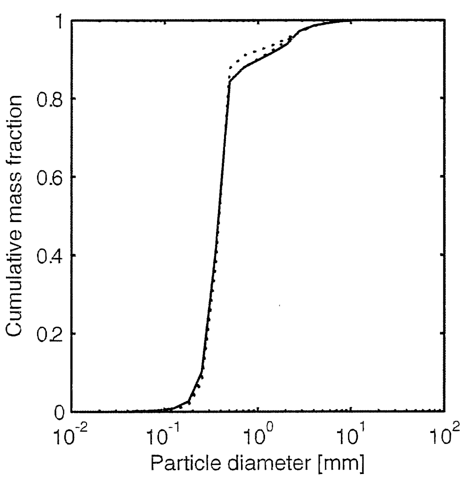


Figure 12 Cumulative size distributions of samples taken at 0.56 m above the primary air distributor (dotted lines) and an ash sample taken from the bottom ash container (solid line), for test with fine coal.

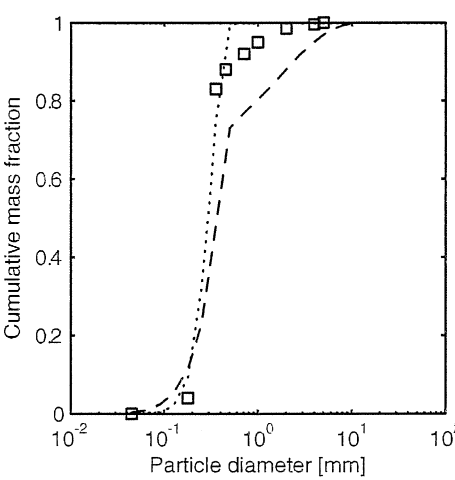


Figure 13 Cumulative size distributions of sample taken at 0.56 m for co-combustion of coal with 67 % dry sewage sludge in present work (dashed line) and of bottom ash from TUHH test of co-combustion of coal and 50 % sewage sludge [10] (squares). The sand is included for comparison (dotted line).

Using the approach of Cammarota et al. [11], the steady state ash particle size distribution in a CFB boiler before the onset of secondary attrition (mechanical attrition of the particle, occurring after completion of the char combustion) can be represented by the primary ash particle size distribution (PAPSD). In other words, the PAPSD is defined as the size distribution of primary ash particles obtained as a result of combustion and primary fragmentation of the fuel (primary fragmentation occurs in association with devolatilization and combustion). Experimental PAPSD data for the fuels used in this work were reported separately by the University of Naples (UN) and by the Technical University of Hamburg-Harburg (TUHH) within the EU project 7220-PR-124 [10], and are shown in Fig. 14. Both universities measured the PAPSD of samples from the same fuel batches as used in these tests. UN followed the procedure described by Cammarota et al. [3], [11], based on batch operation of a bench scale bubbling fluidized bed combustor (0.4 m high), including devolatilization under inert conditions and complete burnout in air, followed by operation of the unit for a few minutes at moderate fluidizing velocities. The size distribution of the fly ash from the exhaust was analyzed by laser scattering granulometer and that of the bottom ash was analyzed by sieving. TUHH determined the PAPSD of dried sewage sludge using the pilot scale CFB combustor described by Klett et al. [12]. A batch of sewage sludge was burned at 850 °C, using a moderate fluidizing velocity, until complete burnout. The ash was then drained from the bottom of the bed and its size distribution analyzed by sieving. TUHH used a different procedure to identify the PAPSD of the coal: a batch of coal was first burned in an oven (without mechanical stress), and was then subjected to mechanical stress in order to induce primary fragmentation.

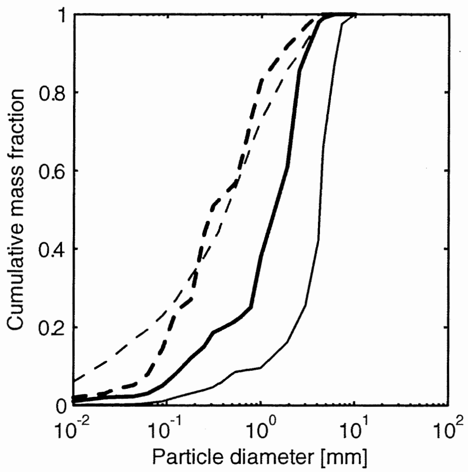


Figure 14 PAPSD of Polish coal III (dashed lines) and of sewage sludge (solid lines) as reported by UN (thick lines) and TUHH (thin lines) [10].

In the case of co-combustion of coal and 67% sewage sludge, PAPSDs from coal and sewage sludge were weighted according to their proportions in the feed to yield a resulting PAPSD for the case studied. The particle size distribution of silica sand was weighted into the mixture, based on the fraction of initial material present in the boiler at the time of sampling at 0.56 m (65 % according to Table 4). Fig. 15 compares the resulting particle size distribution to that of the extracted samples. The weighted size distribution from UN describes the distribution in the bottom bed rather well, whereas there is a gap between these cases and the weighted PAPSD from TUHH.

The steeper size distribution curves for the samples taken at 3.7 m and 7.9 m, shown in Fig. 16, compared to the sample taken at 0.56 m, shown in Fig. 15, suggest that the fraction of sand in the bed material was higher in the transport zone of the furnace than in the bottom bed. More initial bed material (78-82 %) was left in the boiler when transport zone samples were taken than at the bottom bed sampling. However, this does not give the entire picture. The fluidization velocity exceeded the terminal velocity of the major part of the sand particles, thus the fraction of sand was increased in the circulated material compared to the bottom bed. The solids in the transport zone appear to contain about 90 % sand, as estimated by fitting the weighted PAPSD based on data from UN to the sample size distributions (shown in Fig. 16). The large amount of fines in the samples compared to the PAPSD is not explained by the weighted PAPSD. This suggests high ash attrition in the bed.

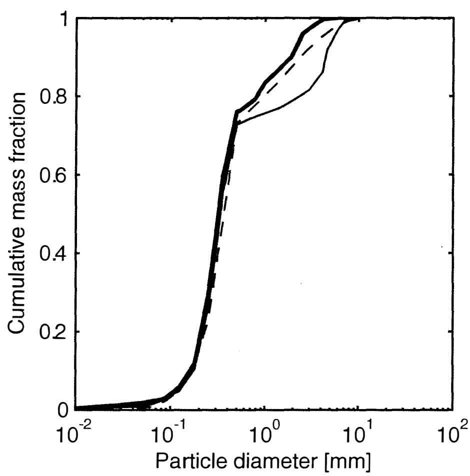


Figure 15 Particle size distribution resulting from weighted (coal/sludge/sand) PAPSD from UN (thick solid line) and TUHH (thin solid line) [10], as calculated for co-combustion of coal with 67 wt% sewage sludge with 65 wt% sand in bed material, compared with particle size distributions of solid sample taken at 0.56 m (dashed line).

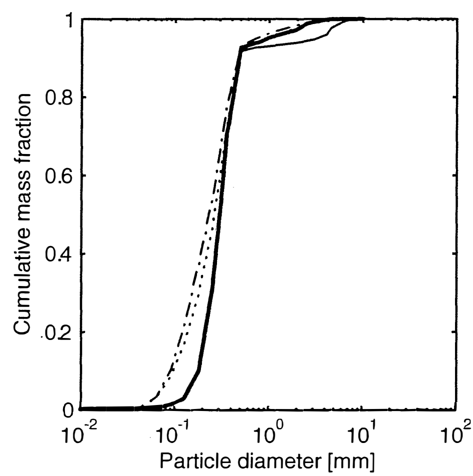


Figure 16 Particle size distribution resulting from weighted (coal/sludge/sand) PAPSD from UN (thick solid line) and TUHH (thin solid line) [10], as calculated for co-combustion of coal with 67 wt% sewage sludge with 90 wt% sand in bed material, compared with particle size distributions of solid samples taken at heights 3.7 m (dotted line) and 7.9 m (dash-dotted line).

Fig. 17 compares the results from sieving analysis of samples taken in the splash zone during combustion of coal and co-combustion of coal with 67 % sewage sludge. Fresh sand is also included in the figure. It is evident that sand contributed greatly to the size distributions. The size distribution of the dry sewage sludge was originally narrower than that of the coal (as shown in Fig. 2), but, as discussed above, it appears that attrition caused a more rapid widening of the sludge ash distribution. The peak in the curve around the sand peak (at approximately 0.1-0.5 mm) is broader for the case with 67 % sewage sludge than for coal combustion, but both peaks are shifted towards coarser particle sizes. Part of the material in the coarser part of the peak could be ash particles that have been attrited to a particle size close to that of the sand. Another part of the broadening could be an effect of the coarsest sand particles being left in the bottom bed as the rest of the sand was circulated. A large part of the bed solids consisted of sand. For this reason, slight changes in the fluidization velocity in the region of the terminal velocity of the sand yielded significant differences in the distribution of the bed material between bottom bed and circulating solids. The fluidization velocity for the case of coal combustion exceeded that of the case of 67 % sludge with 0.5 m/s, which led to entrainment of a larger part of the sand from the bottom bed. Using a simple estimation, only particles whose terminal velocity is exceeded by the primary air velocity were assumed to be entrained from the bottom bed. Approximately 29 wt% of the sand particles then remained in the bottom bed for the case of co-combustion of coal with 67 % sludge, as compared to 18 wt% for the case of combustion of coal. The difference in the sieving analysis results of the solids in the transport zone (above the bottom bed) between combustion of coal and co-combustion of coal with 67 % sludge in the feed is illustrated in Fig. 18. Fresh sand is included for comparison. The increased amount of fines generated in co-combustion with sewage sludge is obvious.

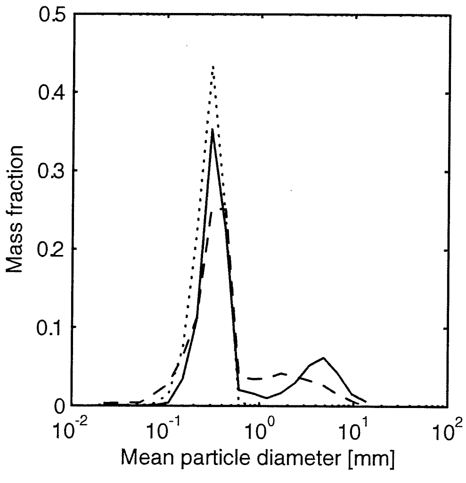


Figure 17 Mass fraction of material on each sieve vs. mean particle diameter in the sieving interval for samples extracted in the splash zone at 0.56 m above the primary air distributor. Coal combustion (solid line), combustion of coal with 67 % sewage sludge (dashed line), and sand (dotted line).

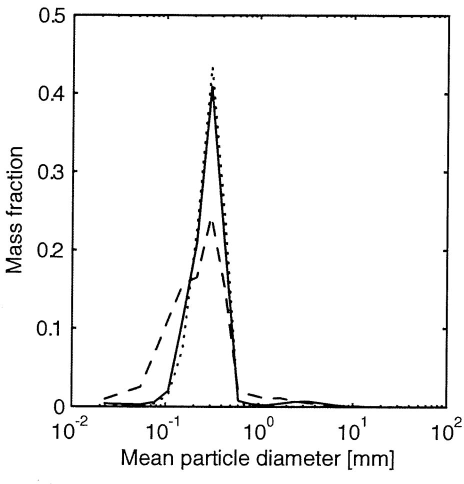


Figure 18 Mass fraction of material on each sieve vs. mean particle diameter in the sieving interval for samples extracted at 7.9 m above the primary air distributor. Coal combustion (solid line), combustion of coal with 67 % sewage sludge (dashed line), and sand (dotted line).

The widening of the bed material size distribution with increasing sludge supply was quantified by comparison of the mass fraction of fine solids (smaller than $d_{p,max,fine}$) and coarse solids (larger than $d_{p,min,coarse}$), as illustrated in Fig. 19.

Figs. 20 and 21 illustrate the widening of the bed material size distributions with increasing sludge supply. The limiting diameters ($d_{p,max,fine}$ and $d_{p,min,coarse}$) were chosen as follows: >99 wt% of the sand has d_p<0.500 mm, and particles with d_p>0.125 mm do not exit with the fly ash. Data for sand are included in the figures for reference. Increased sludge supply leads to a larger amount of fines throughout the furnace, although the effect is only noticeable for sludge fractions >30 wt%. In the transport zone of the furnace (at 3.7 m and 7.9 m), the fraction of coarse material also increases with increasing fraction of sludge in the fuel mix. This is most probably due to the lower density of the sludge ash as compared to the coal ash, originating from the differences in ash structure. Thus, a sludge ash particle is larger than a coal ash particle with the same terminal velocity. The sludge supply has no clear effect on the amount of coarse solids in the bottom bed. During the tests with pre-sieved coal, the fraction of fine solids (<0.125 mm) was 0.4-0.5 % at 0.56 m, 2-3 % at 3.7 m and 2 % at 7.9 m. The fraction of coarse solids varied between 14-24 % at 0.56 m, 4-5 % at 3.7 m and 2-3 % at 7.9 m.

Comparison between the size distributions of the samples extracted during the tests with pre-sieved coal showed a visible difference in combustible particles, which were coarser for the tests with coarse coal. Any difference between the produced ashes was diluted by the high sand content in the bed material.

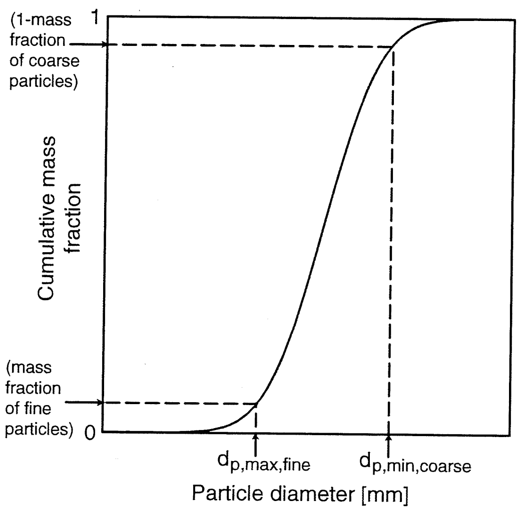


Figure 19 Illustration of the fine and coarse fractions from a particle size distribution

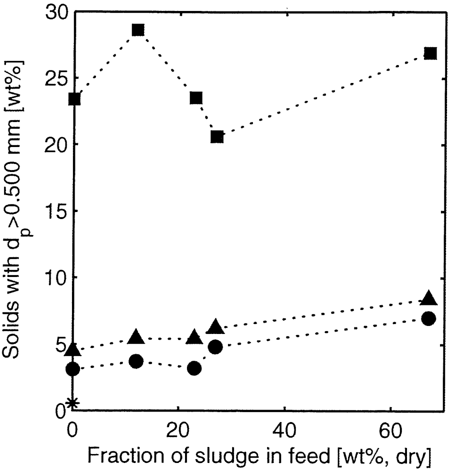


Figure 20 Variation in fraction of bed particles with d_p>0.500 mm with increasing sludge supply at 0.56 m (squares), 3.7 m (triangles) and 7.9 m (circles) above the primary air distributor. The asterisk corresponds to silica sand.

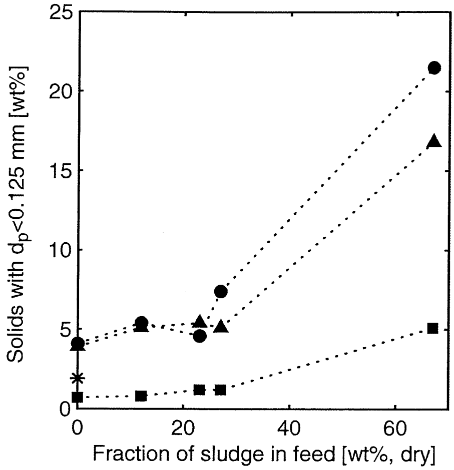


Figure 21 Variation in fraction of bed particles with d_p<0.125 mm with increasing sludge supply at 0.56 m (squares), 3.7 m (triangles) and 7.9 m (circles) above the primary air distributor. The asterisk corresponds to silica sand.

Gas analysis

The axial concentration profiles of O_2, CO_2, CO, and total hydrocarbons measured in the furnace did not differ dramatically between the co-combustion tests (series A), as shown in Fig. 22. No significant variation in the O_2 concentration was measured along the furnace height. However, in the lower half of the furnace, the measured concentrations of CO and total hydrocarbons were slightly higher with sludge present in the fuel than with coal only. This indicates a higher release of volatiles above the bottom bed when sludge is fed to the boiler. The volatiles burn as they are transported towards the furnace exit, thus raising the temperature in the top of the furnace with increased sludge supply, as reported in Table 3.

According to the cross-sectional gas analysis, the variations in concentration of O_2, CO_2, CO and total hydrocarbons were rather large within a plane, particularly in the middle section of the furnace. The results of the cross-sectional measurements of CO and total hydrocarbons, for combustion of coal and co-combustion of coal with 67 % sewage sludge are shown in Figs. 23-26. Figs. 23 and 24 show, as previously noted from the axial concentration measurements, that co-combustion with sewage sludge gave higher concentrations of CO throughout the furnace. Furthermore, co-combustion with sewage sludge resulted in higher concentrations of hydrocarbons in the transport zone of the furnace, as shown in Figs. 25 and 26, but the sludge supply did not influence the hydrocarbon levels in the bottom bed. The concentrations of CO and total hydrocarbons in the lower part of the furnace (at 0.67 m) decreased from the front wall, where the fuel was fed, to the rear wall, where the circulating bed material is returned to the boiler. The concentrations were also higher in the centre positions (from front to back wall) than along the side walls. Higher in the furnace, the levels were also highest at the front wall, except in the centre position at 3.7 m, where they were higher at the back wall. This was possibly an effect of changes in the gas flow pattern caused by the secondary air injection at 2.1 m from the front and back walls. No significant difference in O_2 or CO_2 concentrations was noted when comparing coal combustion and co-combustion with sewage sludge. In the top of the furnace, the O_2 concentrations were highest at the back wall, where the furnace exit is located. At lower heights, the oxygen was irregularly distributed, and in the bottom the concentrations were close to zero. In the bottom of the furnace, the CO_2 levels were higher at the back wall, while they were slightly higher at the front wall in the bottom of the furnace. For the heights in between, the CO_2 was irregularly distributed.

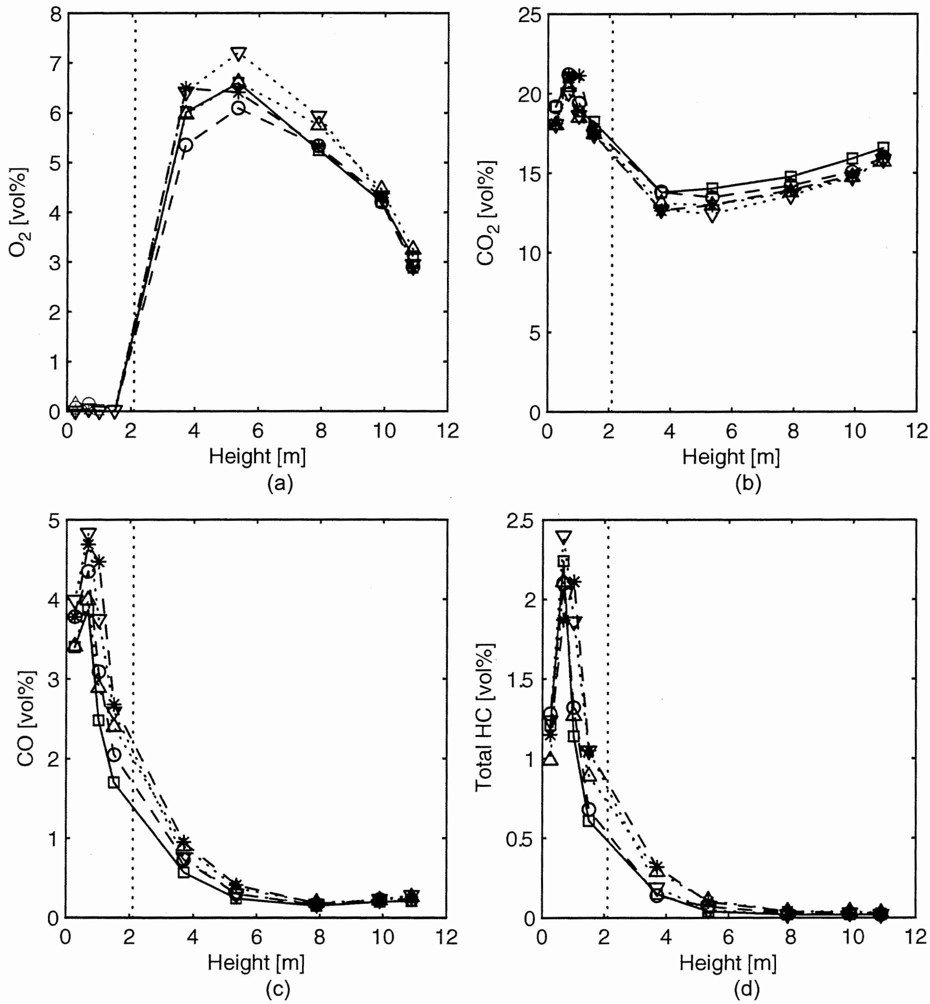


Figure 22 Axial profiles of O_2 (a), CO_2 (b), CO (c) and total hydrocarbons (d) in the furnace from co-combustion tests. Coal only (solid line, squares), 12 % wet sludge (downward triangles), 23 % wet sludge (upward triangles), 27 % dry sludge (circles), 67 % dry sludge (asterisks). Dotted lines for wet sludge and dashed lines for dry sludge in the fuel. Secondary air inlet at height 2.1 m indicated with vertical dotted line.

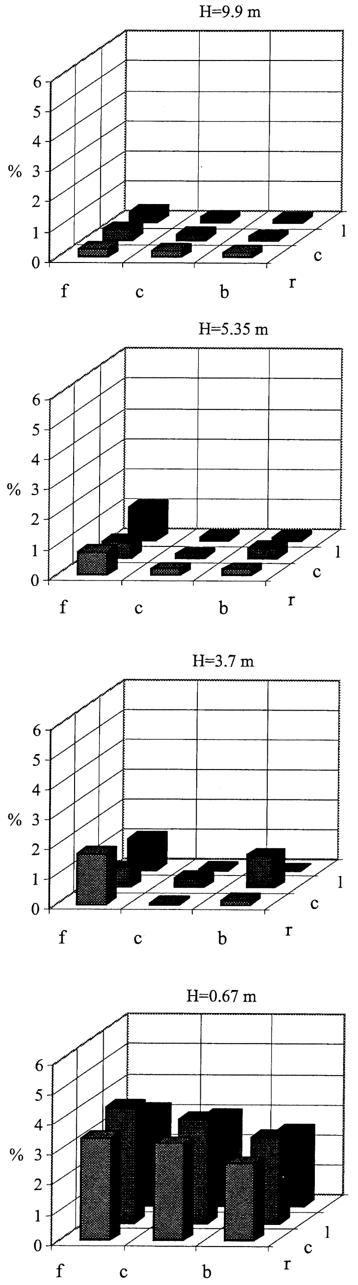


Figure 23 Cross-sectional concentrations of CO, combustion of coal (A1)
f = front, c = center, b = back, r = right, l = left

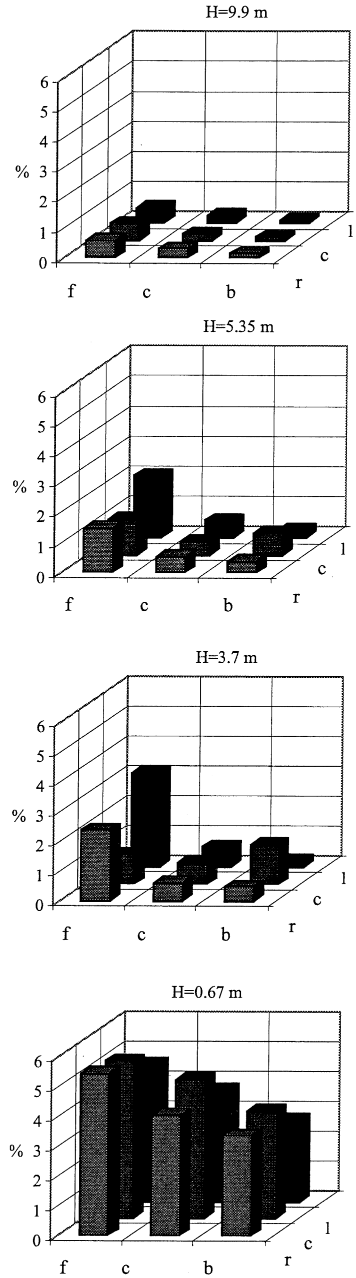


Figure 24 Cross-sectional concentrations of CO, combustion of coal and 67 % sewage sludge (A5)
f = front, c = center, b = back, r = right, l = left

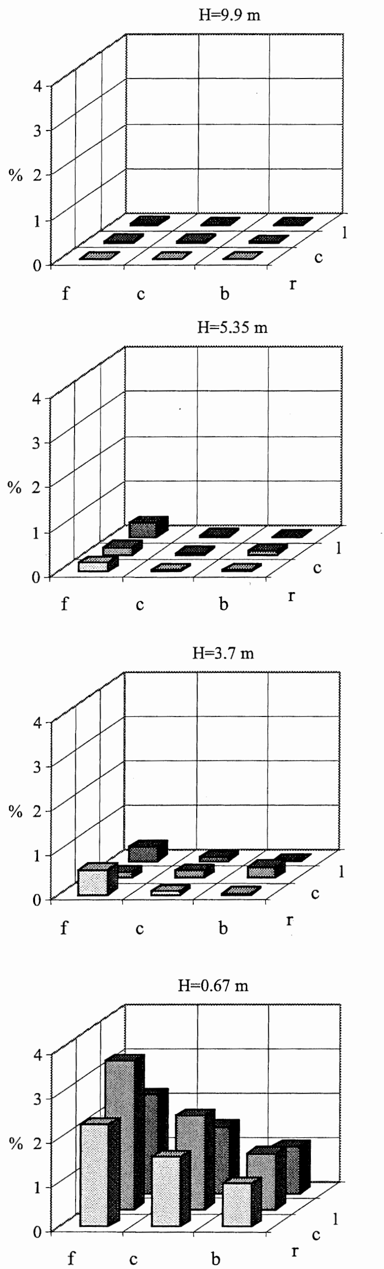


Figure 25 Cross-sectional concentrations of total hydrocarbons, combustion of coal (A1)
f = front, c = center, b = back, r = right, l = left

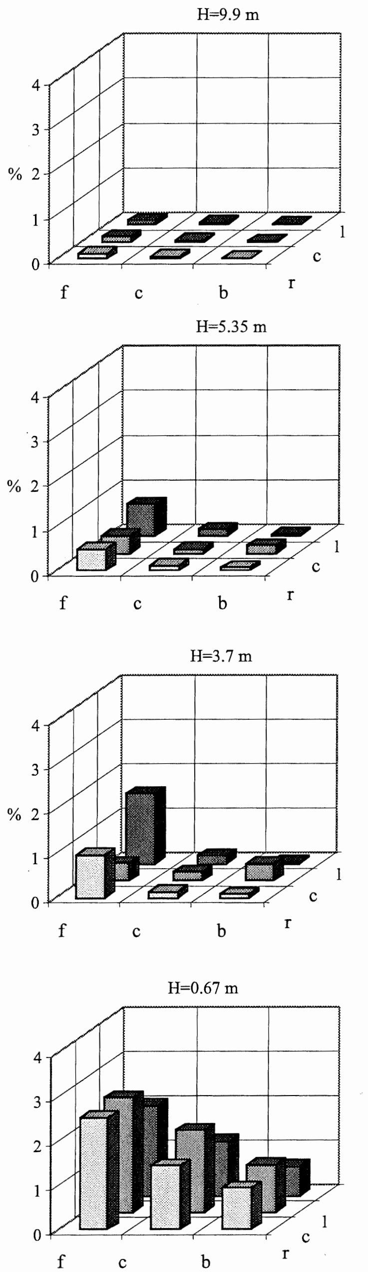


Figure 26 Cross-sectional concentrations of total hydrocarbons, combustion of coal and 67 % sewage sludge (A5)
f = front, c = center, b = back, r = right, l = left

Discussion and conclusions

Tests with co-combustion of coal and sewage sludge (both wet and dry) were performed in a 12 MW_{th} CFB boiler. In order to eliminate the uncertainty related to the wide size distribution of the fed coal in the co-combustion tests, additional tests were carried out with coal pre-sieved into a fine and a coarse size fraction and separately burned. The ash recovery fraction was satisfactory for all tests except for some days during the case of coarse coal combustion.

Some conclusions concerning the influence of co-combustion of coal with sewage sludge on the solid phase and combustion in the furnace can be drawn based on the results:

As expected, the higher ash content in sewage sludge compared to coal resulted in increasing fly ash flows and lower combustible content in the fly ash with increasing fraction of sludge in the fuel mix. The bottom ash flow and combustible content, on the other hand, appeared to be more sensitive to feed coal size distribution than to the sludge supply.

Comparison of the size distributions of the solid samples extracted from the furnace with experimental PAPSD data, in the case of co-combustion of coal with a high fraction of sludge in the feed, indicated a high degree of ash diminution. Compared to coal combustion, co-combustion of coal with sewage sludge resulted in a higher amount of fines throughout the furnace. In theory, the increased solids concentration in the transport zone of the furnace following from the higher amount of fines leads to a more efficient heat transfer to the walls. Furthermore, a higher flow of externally circulating solids is expected, provided that not all the additional fines leave with the fly ash.

The fraction of coarse material in the transport zone of the furnace also increased with increased sludge supply, most likely due to the lower density of the sludge ash as compared to coal ash. These phenomena both contributed to widening of the solids size distributions throughout the furnace with increasing fraction of sludge in the fuel mix.

The effect of the entering coal size distribution on the size distribution of the inert ashes was negligible compared to that of the sludge fraction in the feed. However, the size distributions of the combustible solids in the bed material were dependent on differences in feed size distribution of the coal rather than on the sludge supply.

Considerable size segregation occurred between the bottom bed solids and the bed material entrained by the fluidizing gas. The size distribution of the make-up bed material (silica sand) was such that most of it was entrained from the bottom bed. Consequently, sand constituted the major part of the solids in the dilute transport zone, and probably also in the externally circulating flow.

The increased ratio of volatiles to char in the fuel mix during sludge addition affected the distribution of the combustion in the boiler. The redistribution of gases was illustrated by the increased concentrations of CO and total hydrocarbons in the transport zone in the case of high fractions of sludge in the feed, although no significant difference in O_2 or CO_2 concentrations was visible. The larger amount of released volatiles burned above the bottom bed, thereby elevating the temperature in the top of the furnace.

Although substantial attrition and generation of fines was shown to take place during co-combustion of coal with sewage sludge, the quantification of the attrition was complicated by the fact that steady state for the particle phase was not yet reached when solids sampling was performed. This also eliminated the possibility of comparing the results with results from attrition modelling, as the composition of the bed material at the start of each test was uncertain.

The results presented above are entirely applicable to co-combustion of coal and sewage sludge in full-scale CFB boilers. The major differences compared to coal combustion are: increased fly ash flows, higher concentration of fines in the furnace and higher temperatures in the top of the furnace caused by increased volatiles combustion above the bottom bed.

Acknowledgements

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