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Abstract

Both pollution control and energy efficiency are the actual challenges of flue gas cleaning systems in biowaste to energy plants as well as in waste incineration. Optimization and refurbishment of multi step wet flue gas cleaning systems need detailed knowledge on the process considering both particle phase changes and the gas phase. Hence, for a first time, the flue gas cleaning process of an incinerator was studied in detail both considering particles elimination and particles formation. Particles sampling on impactor substrates allowed to determine dust particles composition in dependence on particle size. Gas phase / particle phase interaction in the flue gas cleaning system was studied and the origin of the dust particles emitted with the clean gas was determined. Being an operations mode with peak dust release, soot blowing was studied in addition to normal operation.

At GKS flue gas cleaning plant, the first step is a cyclones array (multiclone) which icauses 13% of the energy consumption of the induced draft. Elimination of the cyclone was shown to be possible, if the furnace can be operated without flue gas recycling. If flue gas recycling has to be maintained, dedusting of the recycle gas has to be established either treating only the recycle gas stream or e.g. recycling gas from the bag filter exit.

Downstream of the multiclone, particle concentration, particle size distribution and particles composition is dominated not by the combustion process, but by the generation pf particles in a spray dryer desiccating the scrubber slurry and by the elimination of particles in the bag filter and in the scrubber. The particles emitted with the off gas are neither generated in the combustion process nor in the scrubber, but in the wet demister which elminates the scrubber's sprayoff.. This gives evidence of inherent safety in case of a contamination of the scrubber due to accidental overload.

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1 INTRODUCTION AND RESEARCH OBJECTIVES

In order to avoid negative effects on human health and on the environment, waste incineration requires flue gas cleaning by the best available technologies. Resulting from the need of environmental protection, stringent emission limits have been installed. About 15 years ago, these emission limits could be reached by rather expensive and energy consuming flue gas cleaning systems involving multiple process units. Nowadays, flue gas cleaning technology focuses both on economy and energy efficiency. New additives allow for simple flue gas cleaning systems removing both acid pollutants, heavy metals and organic trace components in a single step. In combination with SNCR technology to remove nitrogen oxides, these systems are both cheap and energy efficient. This forces the operators of multi-step flue gas treatment plants to optimize their units.

Both optimization and refurbishment need detailed knowledge on the process considering both particle phase changes and the gas phase.

The research objectives of this project are to

- gain insight into dust particle elimination and particle generation in the flue gas cleaning system
- determine dust particles composition in dependence on particle size
- determine gas phase / particle interaction in the flue gas cleaning system
- determine the origin of the dust particles emitted with the clean gas

To get the information required, gas phase and particulate phase of the flue gas were analyzed simultaneously upstream and downstream of each of the main flue gas cleaning units installed at GKS incinerator flue gas cleaning plant.

2 METHODS

In order to yield reliable results, the methods applied had to be chosen carefully. Sampling was the most critical issue because artefacts had to be avoided as far as possible. For analysis standard procedures could be applied

2.1 Sampling

Getting information on particle size distribution, total amount of dust and sampling enough dust for chemical analysis is a difficult task.
Very detailed information on particle size distribution including time resolved information can be obtained by electrical low pressure impactor (ELPI) measurements. The drawback is the range limited to small particles with aerodynamic particle diameters between approximately 0.1 µm and 4 µm. Coarse dust cannot be quantified with the ELPI and the amounts of dust sampled in most cases are too small to allow chemical analysis. Conventional low pressure impactors (e.g. Berner type) have the same drawbacks.
Other particle sizing sampling methods are settling chamber probes and combinations of cyclones with low pressure impactors [Deuerling et al., 2010]. These methods, however, are not standardized.

Therefore we refrained from multi stage impactor sampling and chose the two stage impactor with backup filter “Johnas” developed at Duisburg University. This allowed sampling of three particles fractions (< 2.5 µ, 2.5 – 10 µ and > 10 µm) following ISO 23210:2009 or VDI 2066 Blatt 10 respectively.

2.1.1 Sampling positions

Sampling positions had been chosen in a way to allow characterization of the main advanced pollution control (APC) units. **Figure 1** shows the sampling positions in a scheme of GKS WTE plant.

At GKS, the first APC unit after the boiler is an array of cyclones (“multiclone”) eliminating coarse dust in order to allow flue gas recirculation. Sampling was performed at the duct between boiler and cyclone (1) and behind the cyclone (2). The next unit is a spray dryer which both acts as a quench and serves to desiccate the scrubber slurry. Upstream the spray dryer, a small amount of activated carbon or activated coke is added. For this additive, the spray dryer acts as reaction zone. The additive is eliminated together with virtually all dust in a bag filter. Sampling positions were the duct before (3) and the duct after the bag filter leading to a scrubber (4). The 2 stage scrubber as the next APC unit eliminates HCl, HF and sulphur oxides. It is equipped with a wet demister and a gas reheater. The last sampling position was on the duct after the reheater (5).

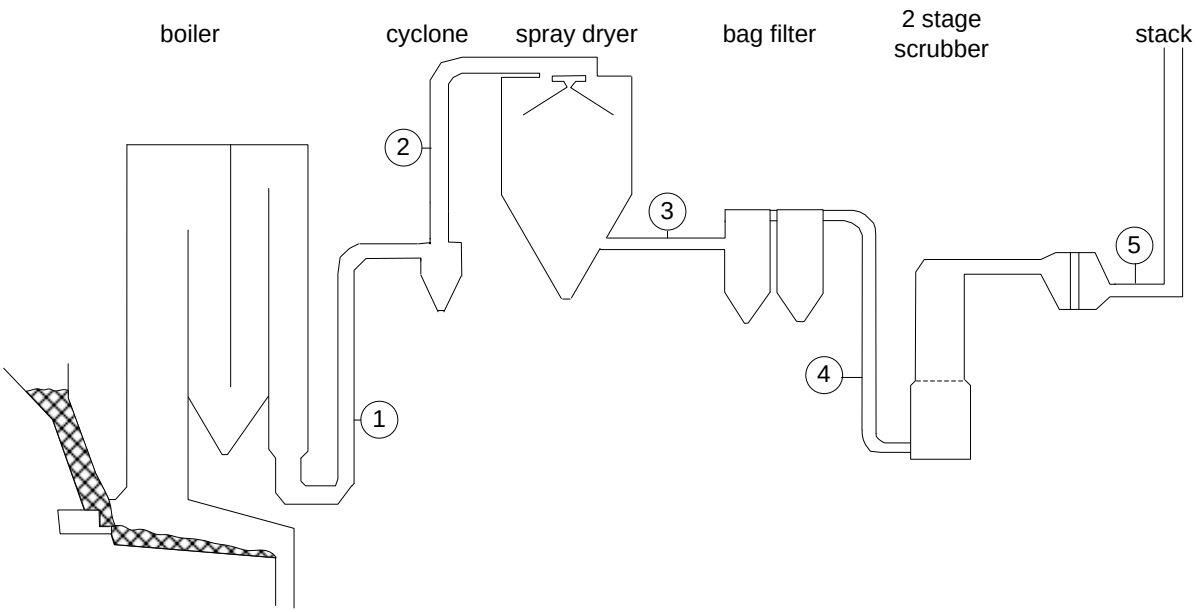


Figure 1: Sampling positions on the flue gas treatment system

2.1.2 Particles sampling method

Particles samples were taken separating sizes in a 2 stage impactor type “Johnas” (Paul Gothe GmbH, Duisburg, Germany). Nominal 50% cut off sizes were 10 µm and 2.5 µm. Particles smaller than 2.5 µm were collected on a backup filter. Excepted on sampling position 3 (behind the spray dryer) the impactor was preheated and positioned “in stack”. At sampling position 3, the duct was inaccessible to the impactor because the sampling port was a small hole instead of a flange. Ample isolation of the sampling port and heating both the sampling line and the impactor to 180°C guaranteed the sampling system temperature exceeding the acid dew point.

Samples were taken iso-kinetically adapting gas velocity at the nozzle by varying only the nozzle diameter because of the impactor requiring a constant flow rate. The load on the impactor substrates being limited to a few milligrams, sampling intervals had to be adapted to the dust concentration expected. Sampling intervals lasted between 1 minute at the boiler exit and 5 h at the stack.

With respect to possible changes in dust concentration and composition between samplings, samples were taken as far as possible simultaneously upstream and downstream of the APC unit under investigation. At the bag filter, this was impaired by the huge difference in dust load which required different sampling intervals before and behind the unit. The short sampling intervals at the bag filter inlet (behind spray dryer) were positioned in the mid of the sampling periods behind the filter.

Triplicate samples were taken before and behind each APC unit investigated; and chemical analysis was made of two pairs of the samples. Thus, multiple results are available on different sampling positions (cf. **Table 1**)

Table 1: Sampling scheme

APC unit	sampling position	number of samples	samples analyzed
	boiler exit	2 + 1*	1 + 1*
cyclone	cyclone exit	5 + 1*	3 + 1*
spray dryer	spray dryer exit	6	4
bag filter	bag filter exit	6	4
scrubber	Stack	3	2

*: one sample was taken during soot blowing (blower # 3, superheater section)

2.2 Analytical methods

Chemical analysis of the flue gas and of the particles collected can be done by standard methods. Although for flue gas analysis both off-line wet sampling and single component online analysers could have been applied, we chose a multi component analyser for flue gas analysis.

The dust samples either could have been analyzed by X-ray fluorescence (RDX) or by acid digestion and spectrometric methods. Because RDX does not allow to determine trace components and because of matrix effects in RDX analysis, we chose to apply staged dissolution of the samples and both ion chromatography and ICP-OES as analytical methods.

The gas phase of the flue gas was analyzed online by FT-IR spectrometry (Gasmet 4000, Gasmet Oy, Helsinki, Finland).

Mass of the dust particles collected on the impactor substrates was determined by weighing after conditioning the samples in a desiccator at room temperature for 24 h. Chemical composition was analysed after stepwise dissolution: step 1 was an aqueous extract which was analyzed for chlorides by ion chromatography. The water soluble part of sulphates and other salts were determined by ICP-OES. The extraction residue containing the fraction insoluble in water was dissolved by microwave-assisted pressure digestion with a mixture of HNO_3, HCl and HF. Analysis of this fraction, again, was done by ICP-OES. On a few substrates the amount of dust collected was insufficient for chemical analysis.

3 RESULTS

3.1 Particle size distribution

Investigating the cyclone and the bag filter being dust eliminating APC units, the total dust load differed much at the sampling positions (cf. **Table 2**). The sample taken during soot blowing exceeds the normal dust concentration by more than an order of magnitude at the boiler exit. Most of the dust released during soot blowing consists of particles > 10 µm, thus the dust concentration difference is much lower at the cyclone exit.

The cyclone efficiently eliminates dust particles > 10 µm. Its effect on the smaller particle fractions is negligible. In the spray dryer, the calcium salts containing scrubber slurry is evaporated to dryness. Both coarse dust particles and fine dust can be expected from the slurry residue. This can clearly be seen in the particle size distribution at the spray dryer exit. The bag filter lowers the dust concentration by 3 orders of magnitude. Although most particles passing the bag filter are smaller than 10 µm, approximately 25% of the dust at the bag filter exit consist of particles > 10 µm.

Wet scrubbers efficiently eliminate particles entering. However they generate a wet aerosol, resulting in new particles being formed depending on the scrubber slurry concentration. At GKS, the scrubber is equipped with a wet demister eliminating most of the sprayoff. As a result, after reheating of the gas, dust concentrations at the scrubber exit are lower than at the entrance. At the scrubber exit, more than 90% of the dust consist of particles < 10 µm and more than 60% of the dust has particle sizes < 2.5 µm.

Table 2: Dust concentration and particle size distribution (mean values)

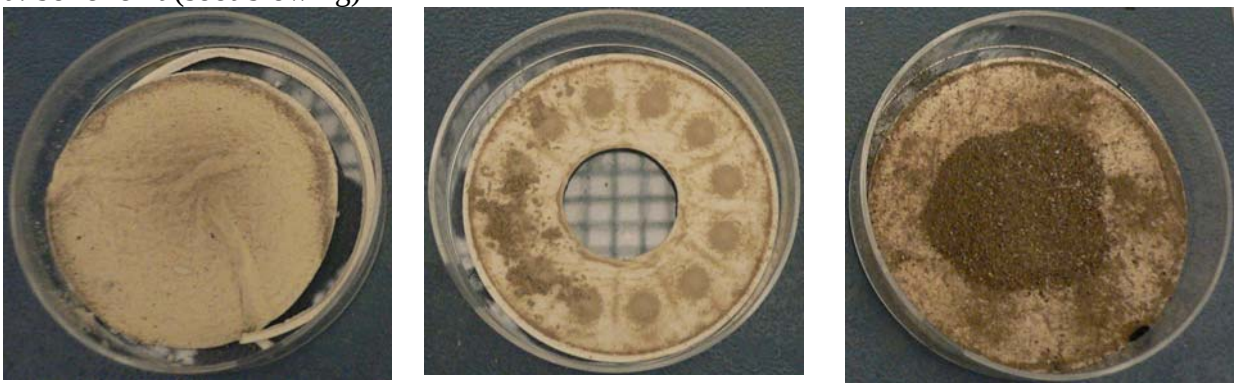
sampling position	**n**	**total dust** [mg/m³ STP]	**< 2.5 µm** [mg/m³ STP]	**2.5 < x < 10 µm** [mg/m³ STP]	**> 10 µm** [mg/m³ STP]
boiler exit	2 (1)*	1870 (25400)*	740 (1650)	250 (1180)*	880 (22500)*
cyclone exit	5 (1)*	1260 (2980)*	1060 (1330)*	160 (1570)*	37 (80)*
spray dryer exit	6	2450	1460	440	550
bag filter exit	6	3,0	1,3	1,1	0,61
scrubber exit (stack)	3	1,7	1,1	0,47	0,14

n: number of samples
*: sample taken during soot blowing (blower # 3, superheater section)

Although the quantification error of the gas volume meters and the errors of weighing are low, the uncertainty of sampling is quite high, especially for the samples at high dust load where sampling time intervals lasted only 1 minute. In these cases, setting up the correct gas flow took up to 10 % of the sampling time. Under normal conditions, carefully performed dust sampling following a sampling grid with multiple sampling positions on multiple axes can reach accuracy up to 10%. As we had to pertain to a single sampling position and with the short sampling intervals, the sampling uncertainty considering total dust load is estimated to be approximately 25%. The uncertainty of the particle size distribution due to weighing errors and due to imperfect isokinetic conditions during sampling is estimated to additional 15%, excepted for the samplings at the boiler exit, where an overload of the impactor's first stage (> 10 µm) occurred when sampling during soot blowing and may have occurred at the other two samplings due to the low stickiness of the dust (cf. Figure 2).

Backup filter (< 2.5 µm) **Stage 2 (2.5 < x < 10 µm)** **Stage 1 (> 10 µm)**

a: boiler exit (soot blowing)



b: boiler exit (normal operation, low impactor load)

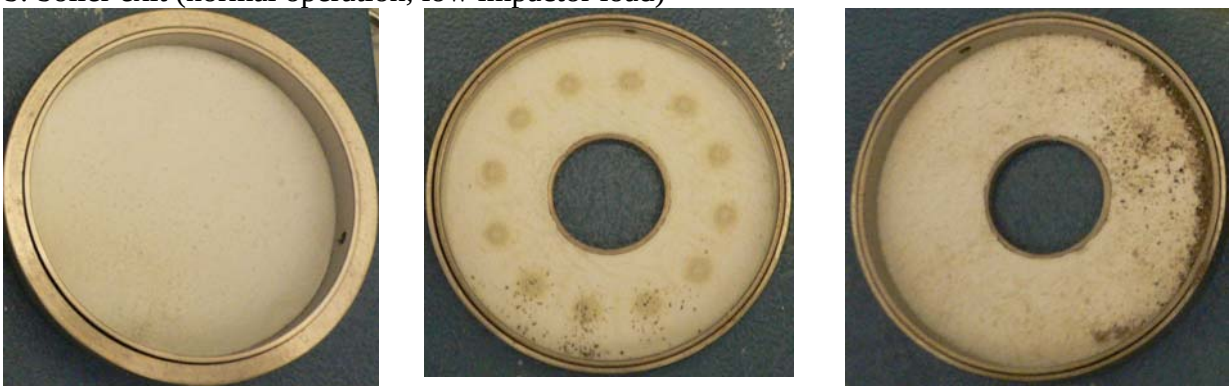


Figure 2: Examples of impactor stages after sampling

3.2 Dust composition

Dust composition varies largely in the course of the flue gas cleaning system. The following figures show the mean dust composition at the sampling positions. Although the chemical analysis of the samples in general yielded reproducible results, it has to be considered that minor constituents are being suppressed because of the limits of quantification in samples where the

amount of dust collected was low. Also, the results of silicon analyses are not very reliable because of the fact that quartz fibre filters had to be used as substrates in the impactor. This can have led to contamination of the dust collected.

At the first APC stages the dust composition depends on waste composition and the pollutant release in the furnace. Thus, especially for the coarse dust fraction, the composition at the boiler exit is complex. A considerable amount of the small particles (< 2.5 µm) is made up of condensed salts and therefore there is a considerable shift in composition between the particles sizes (Figure 3).

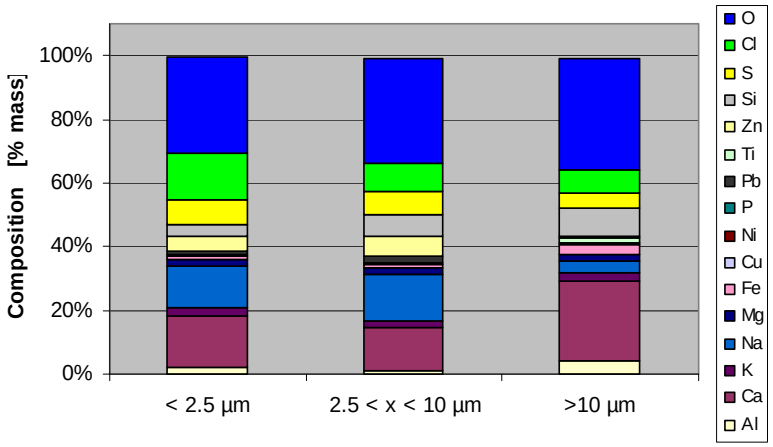


Figure 3: Mean dust composition at the boiler exit (without soot blowing, n=2)

The fine dust particles (< 2.5 µm) collected at the boiler exit contain both sodium and calcium salts, whereas the particles > 10 µm contain higher amounts of calcium and aluminium oxides. The composition of the fine dust particles is collected is not very typical, usually we observed higher sodium and potassium content and lower calcium, aluminium and silicon in particles < 1 µm [Deuerling et al., 2009]. Even considering the uncertainty of the silicon analysis, the silicon oxide content in the particles > 10 µm is significantly higher than in the small particles.

The multiclone eliminates large particles. Therefore, at the cyclone exit the particle composition is less size dependent than at the boiler exit. With a high content of sodium and potassium salts, the composition of the fine particles collected after the cyclone corresponds better to our earlier findings (cf. Figure 4).

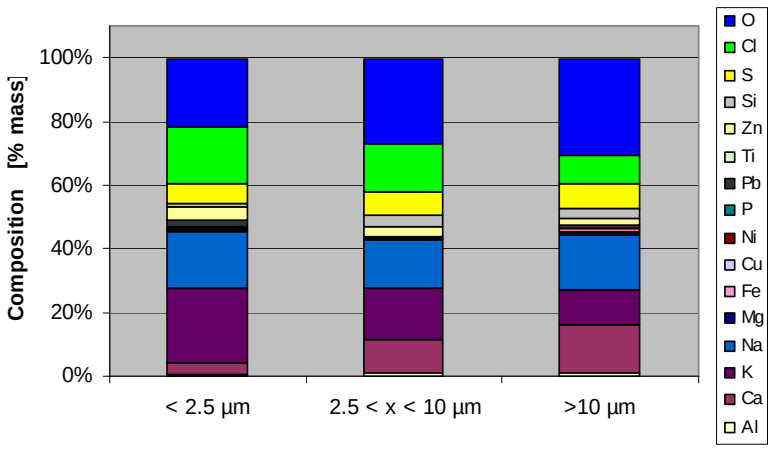


Figure 4: Mean dust composition after the multiclone (without soot blowing, n=6)

In front of the spray dryer, lignite coke is injected into the flue gas. In the spray dryer, the calcium chloride and calcium sulphate containing scrubber slurry is added, and dried. This shifts

the dust composition towards calcium salts (cf. Figure 5). Only the small particles fraction still contains more sodium and potassium than calcium.

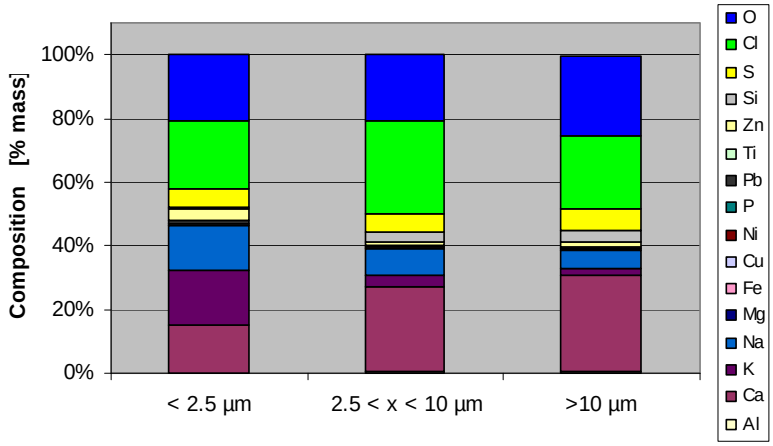


Figure 5: Mean dust composition after the spray dryer (without soot blowing, n=6)

In the bag filter most of the dust is eliminated and only a small fraction is passing through. Obviously, this again means a separation in particle size. Heavy metals, e.g. zinc, are enriched in the dust at the bag filter exit (cf. Figure 6).

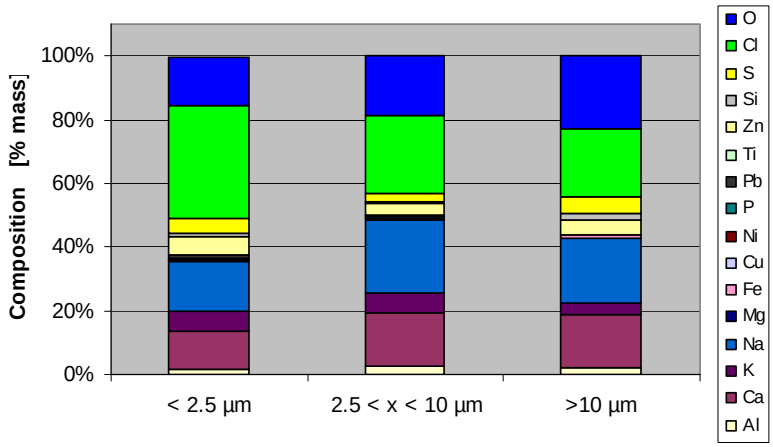


Figure 6: Mean dust composition after the bag filter (without soot blowing, n=6)

At the exit of the scrubber/demister combination, the dust composition again is changed: the heavy metals are eliminated and both the sodium, the potassium and the sulphur concentrations are lowered (cf. figure 7). This can be attributed to particle elimination in the scrubber and generation of new particles with the spray-off.

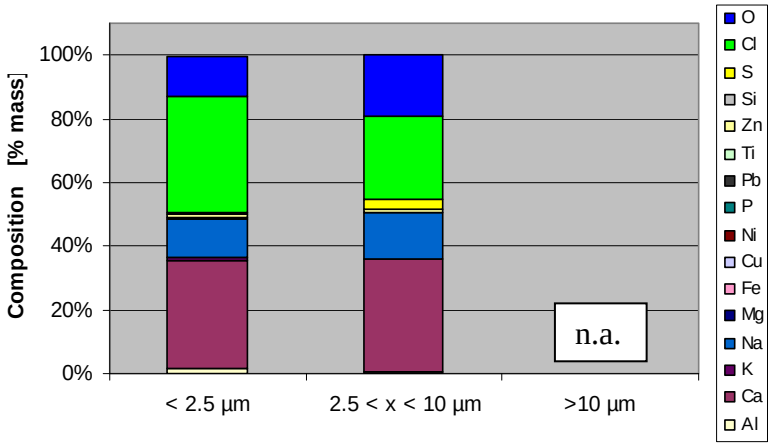


Figure 7: **Mean dust composition at the stack, i.e. after scrubber, demister and reheater (without soot blowing, n=3) (sample of particles > 10 µm to small to analyse)**

3.3 Gas phase composition

As with the dust, gaseous pollutants concentrations vary depending on waste composition and on the combustion process. Gas phase composition was measured simultaneously to the dust sampling; however, the measurement was continued al least for 1 hour. The mean values of corresponding measurement intervals are presented in Table 3.

As to be expected, gas composition is not affected significantly in the cyclone. However, in the spray dryer approximately 25% of HCl is eliminated, which indicates residual acid capacity in the flue gas cleaning slurry being evaporated. The bag filter, again, does not affect gas composition. The main step for elimination of HCl and SO_2 is the wet scrubber. At the scrubber exit emission limits are kept without problems; in fact they are lower than 10 % of the emissions limits.

Table 3: HCl and SO_2 concentrations measured (corresponding mean values)

	SO_2 [mg/m³ STP, dry]	HCl [mg/m³ STP, dry]
Boiler exit	390	860
Cyclone exit	380	820
Cyclone exit	320	940
Spray dryer exit	290	680
Spray dryer exit	280	750
Bag filter exit	280	720
Bag filter exit	300	680
Scrubber exit	4	< 1

4 DISCUSSION

4.1 Dust concentration and particle size distribution in normal operation

Dust concentration in the crude flue gas can vary largely on a short time scale. Hence, concerning the effects of the flue gas cleaning units on the particle concentration and the particle size distribution, it is important to compare samples taken simultaneously. Thus, the bar graphs in Figure 8 to Figure 11 represent the mean of 3 samples each instead of a mean of the 6 samples taken at the same sampling positions between flue gas cleaning units. Exceptions are indicated. The results are being discussed in the order of the flue gas cleaning units.

Multiclone

As mentioned earlier, the multiclone mainly eliminates coarse particles. The error bars in Figure 8 indicate the difference between the two samplings. The concentrations of particles smaller than 10 µm are not changed significantly in the cyclone. This results in a change of total dust load of approximately 45%. With a flue gas volume stream of 42.000 m³/h STP (including the recycle gas), the mass flow of dust separated in the multiclone at the time of sampling was 33.5 kg/h. This corresponds well to the amount of dust separated in the cyclone: in 2005 the dust separated in the cyclone was collected several times for 24-h in order to determine the mean mass flow rate [Müller, 2005]. These tests yielded a mean mass flow rate of 50,4 kg/h, somewhat higher than the value we determined on the short time sampling. One reason is the variability of dust concentration; the other is the effect of soot blowing, which is performed every 8 hours. **Table 2** shows a huge increase in dust particles > 10 µm during soot blowing in the superheater zone. The multiclone works without problems at this high dust load. The mass flow of dust separated in the cyclone peaked up to 940 kg/h during action of the blower # 3, which is situated between the final two stages of the superheater.

In the sample taken at the boiler exit, there seems to be an increase in small particles concentration during soot blowing. Most probably, this is a sampling artefact due to overloading the impactor used for sampling. Particles > 2.5 µm could be detected by microscope in the dust collected on the back up filter.

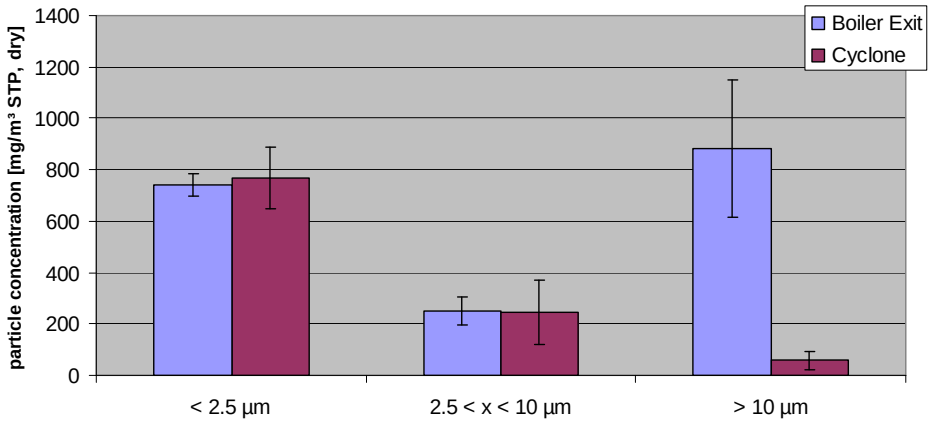


Figure 8: **Particle size distribution before (boiler exit, n=2) and after the multiclone (cyclone, n=2)**

Spray evaporator

The slurry from the scrubber evaporated in the spray dryer has a solids content of 3 – 4 mass-%. Very large particles (>> 10 µm) generated from the slurry drop to the dryer's discharge hopper. Smaller particles are entrained with the flue gas flow and lead to an increase in dust load. Figure 9 shows the particle size distribution of the corresponding samples. The mass flow of particles entrained was 17 kg/h of particles > 10 µm and 12 kg/h of particles > 2.5 µm and < 10 µm. Even the particles < 2.5 µm showed an increase in mass flow of 5 kg/h. It was not expected to yield a significant increase in fine dust from the spray dryer, because the minimum size of particles generated in the dryer should be approximately the size of the particles in the slurry. These were expected to have a size of > 2.5 µm. However, the increase of fine dust corresponds well to the amount of lignite coke added (6 kg/h) upstream of the spray dryer.

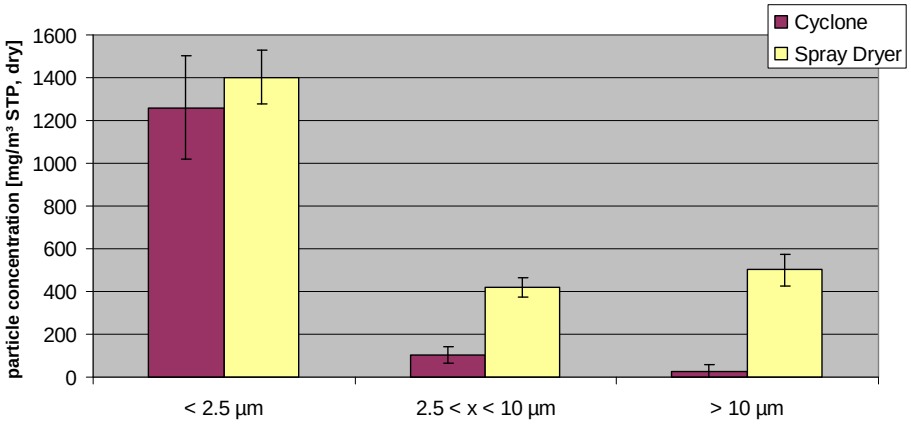


Figure 9: **Particle size distribution before and after the spray dryer ("cyclone" and "spray dryer", respectively)**

Bag filter

The bag filter is the main dust separator in the flue gas cleaning plant. Bag filters are characterized by their high efficiency in dust removal. Because of the filter cake building up on the fabric fine dust particles are being retained well, even if the filter cloth has larger pores than the smallest particles to be retained. However, in order to limit the pressure drop, the filter cake has to be removed by back flushing the bag filter with a jet pulse of compressed air regularly.

After the jet pulse, during build-up of the new filter cake, the filter is more permeable to fine dust particles than during most of the operational time. Large particles cannot enter the filter cloth. As a consequence, large (> 10 µm particles found downstream of a bag filter must either have penetrated small holes in the cloth, e.g. the stitches from sewing the filter bag or the particles must have been generated behind the filter from smaller particles by agglomeration.

Figure 10 shows the effect of the bag filter on particle concentration and particle size distribution. The concentration downstream of the filter being very low, the size distribution is shown in an insert. Basing on the experimental data, calculation of the mass flow of dust eliminated in the bag filter gave 93 kg/h. The mass flow of dust into the bag filter depends on the solids content of the slurry fed to the spray dryer, on the particle size distribution generated in the dryer and on the amount of slurry evaporated. The slurry feed rate depends on the flue gas enthalpy, because the spray dryer is operated as a quench using the slurry feed rate to control the flue gas temperature in the bag filter. Recalculating the expected mass flow rate gave 91 kg/h particulate matter entering the bag filter (50 kg/h dust after multiclone + 35 kg/h as a typical value total solids from the spray dryer + 6 kg/h active coke added). Considering that in case of the bag filter true simultaneous sampling was not possible due to the difference in dust load, the mass flow rate calculated is reasonable.

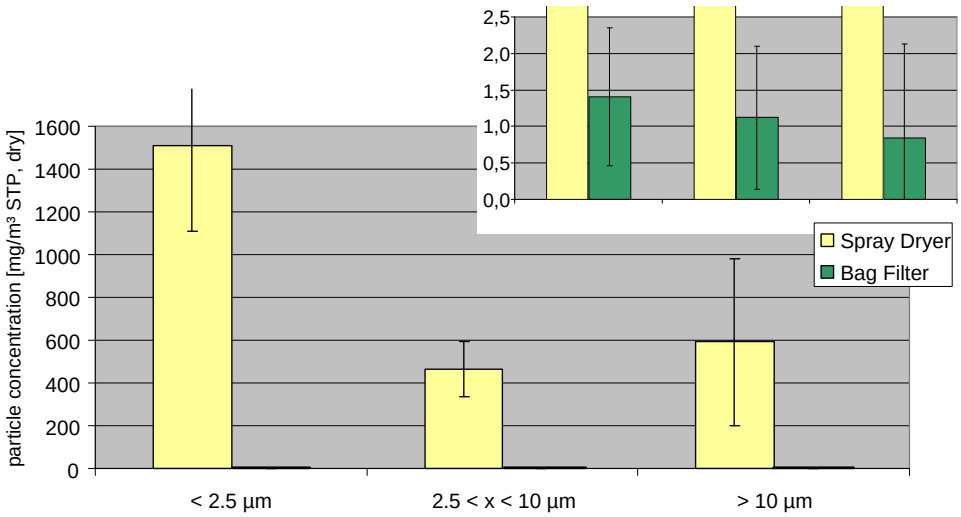


Figure 10: **Particle size distribution before and after the bag filter ("spray dryer" and "bag filter", respectively), the oprdinate in the small figure is adapted to show the amount of particles behind the filter.**

Two Stage scrubber

On one hand, the scrubber could be able to add a large amount of dust because of entrainment of scrubbing fluid droplets. On the other hand, wet scrubbers are known to be efficient in eliminating dust from a gas stream being able even to catch ultrafine dust particles by agglomeration with wet spray droplets in the scrubber. In total, the impact of the scrubber with its wet demister and reheater depends largely on the efficiency of the demister. Figure 11 shows the scrubber to lower further the already low dust concentration which comes from the bag filter. The difference of the concentrations of small (< 2. µm) particles entering and leaving the scrubber is smaller than for the larger particles. This might lead to the assumption of a lower elimination efficiency for small particles. However, as described, the efficiency should be high for both particle size classes. Whether the reason for this difference between the particle size

classes results from differences in elimination or from differences in particle formation by spray off from the demister only can be determined by chemical mass balancing.

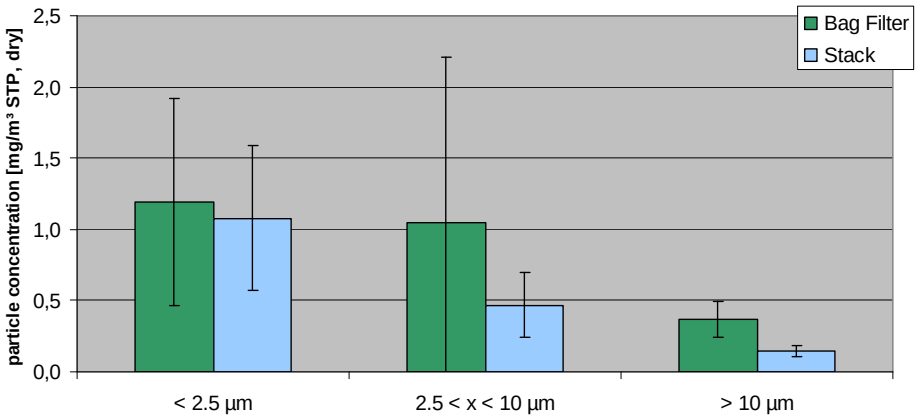


Figure 11: Impact of the 2 stage scrubber unit on the dust particle size distribution

4.2 Shifts in particle composition in normal operation

The results presented in chapter 3.2 already showed the dependence of particle composition on particle size distribution and on the sampling position.
Because of the day to day variability in the plant, shifts in particle composition in the flue gas cleaning units can be estimated much better when selecting samples taken simultaneously than basing on mean values covering all samples available.
Again, in the diagrams following, the data are arranged in the sequence of the flue gas cleaning process units. The cumulated bar graphs show changes in composition, not in the concentration of the components. Therefore, the particle concentrations (figures 8, 9, 10 and11) are given as inserts once more, thus allowing to estimate concentration changes.

Multiclone
Unlike the typical composition of particles < 2.5 µm at the boiler exit, which is dominated by sodium and potassium chlorides and sulphates (many measurements in the boiler section cf. e.g. [Deuerling, 2010]), the particles < 10 µm sampled at the boiler exit seem to have contained more calcium than potassium. The particles < 10 µm collected downstream of the cyclone, however, showed the expected composition (Na + K >> Ca). Unfortunately, there was only one sample of particles collected at the boiler exit at normal operation in this campaign available for chemical analysis. This is the reason why it is not possible to determine why the calcium/potassium ratio seems to be switched between the samples from the boiler exit and the exit of the multiclone. The most probable explanation is a certain amount of calcium-rich large dust particles (> 10 µm) entrained to the 2nd stage of the impactor and to the backup filter because of a handling error or because of impactor overload. This hypothesis is sustained by microscopic examination of backup segments of the backup filter and of the < 2.5 µm impactor substrate, as particles > 10 µm could be identified on both media. A fundamental change in particle composition is not to be expected for the small and medium size particles.

Most of the particles > 10 µm are being eliminated in the cyclone. When differentiating particle sizes > 10 µm, there again is a difference in composition e.g. between the size classes

10 - 20 µm, 20 – 125 µm and particles > 125 µm, the latter being richer in calcium, aluminium and silicon. The fraction between 10 (8) µm and 20 µm in contrast contains more salts, resembling more the fraction < 10 µm (cf. Figure 13). Thus the change in composition of the particles fraction > 10 µm most probably is the result of particle size fractionation in the multiclone.

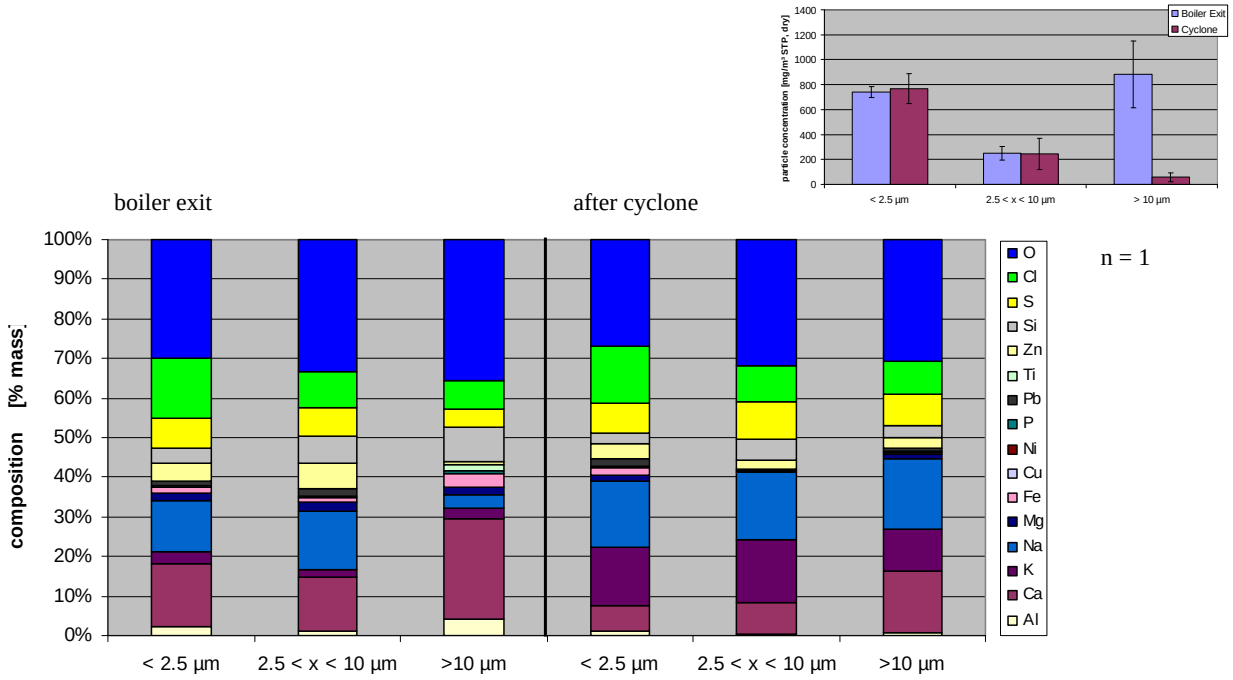


Figure 12: Change in particle composition in the multiclone

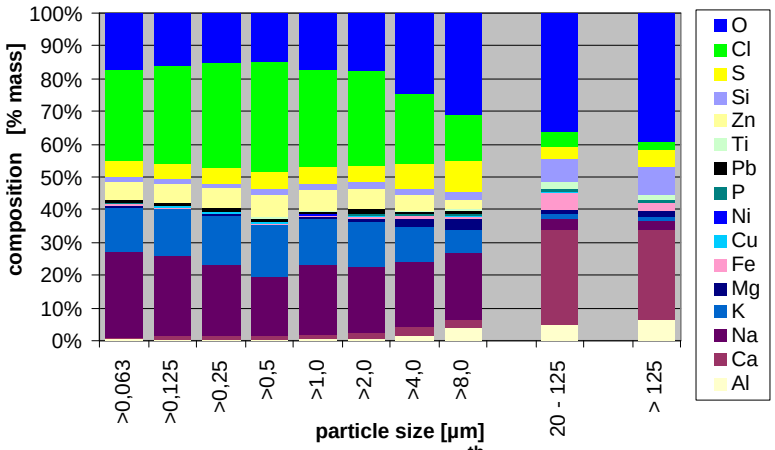


Figure 13: Typical composition of particles in the 4th pass and at the boiler exit [Warnecke and Nordsieck, 2008, adapted]

Spray dryer

In the spray dryer, the scrubber slurry is dispersed into the flue gas stream. The scrubber slurry contains 3 - 7 % of solids residue, mainly calcium chloride and calcium sulphate. The wet aerosol generated dries up yielding particles that represent the chemical composition of the slurry (cf. Table 4). Large particles formed can settle in the spray dryer.
Concurrent to the generation of new aerosol particles, some of the dust entrained with the flue gas is eliminated being caught by the spray and settling.

A tentative mass balance for the spray dryer yields a plausible result:

With the boiler operating at 100% load, the slurry feed rate is almost constant at 980 kg/h. At the sampling period, the slurry solid residue was 3.5 % yielding a solids mass flow rate of 35 kg/h. The dust mass stream at the spray dryer entrance was 56 kg/h (50 kg/h dust leaving the multiclone plus 6 kg/h pulverized active coke), yielding a total solids mass flow of 91 kg/h entering the spray dryer. At the exit of the spray dryer the mass flow of dust entrained was 84 kg/h. The difference of 7 kg/h must have left via the discharge hopper. This value is in accordance to the results of mass balancing experiments at GKS (5 kg/h [Müller, 2005, unpublished])

Most of the particles generated in the spray dryer were larger than 2.5 µm (Figure 14).
As being expected, the dust particles composition was shifted towards calcium salts. Even the small particles < 2.5 µm contained more calcium after the spray dryer indicating the increase of fine particles concentration has to be attributed to small particles generated in the spray dryer. Along with the rise in calcium content, the particle's chlorides content went up in the spray dryer. This is consistent with the slurry composition (cf. Table 4).

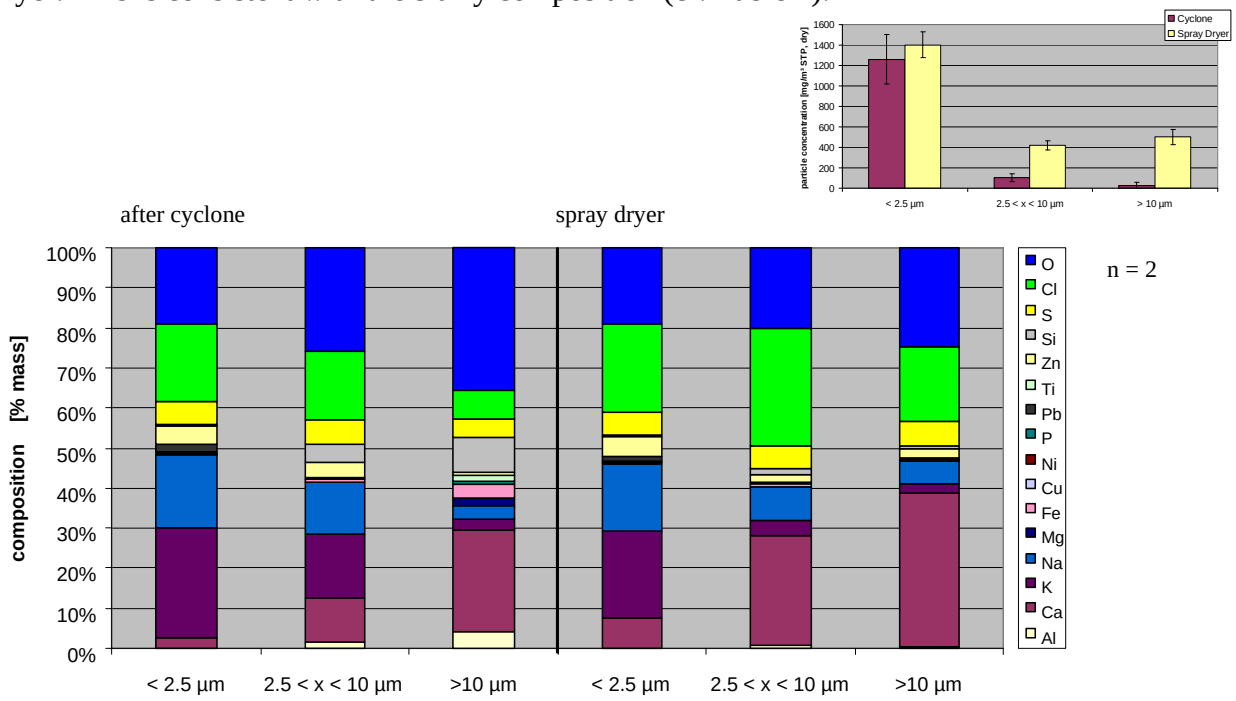


Figure 14: Change in particle composition in the spray dryer

Table 4: Typical analysis of the scrubber slurry

	Mass concentration	
Cl^-	36	g/l
SO_4^{2+}	1,3	g/l
Na^+	0,3	g/l
K^+	< 0,2	g/l
Ca^{2+}	20	g/l
Mg^{2+}	0,2	g/l
Al^{2+}	< 0,1	g/l
Si	< 0,5	g/l
Zn^{2+}	< 0,1	g/l
$CaSO_4$ (solid)	11	g/l

Bag filter

The bag filter eliminated almost all dust particles. The amount of particles > 10 µm was insufficient for chemical analysis. Because of the low dust concentration at the bag filter exit, the sampling period there had to be much longer than at the bag filter entrance. Hence, sampling was not strict synchronous.
At the exit of the bag filter, the results of chemical analysis showed the composition of particles < 2.5 µm and > 2.5 µm to be more similar to each other than to the particles entering the filter (cf. Figure 15). Both fractions contained higher sodium and zinc concentrations than the particles entering. This could be explained by selection of the finest dust particles able to penetrate the filter tissue and agglomerating before or when they leave the filter.
There is no sound explanation of the increase in aluminium concentration in the particles leaving the bag filter.

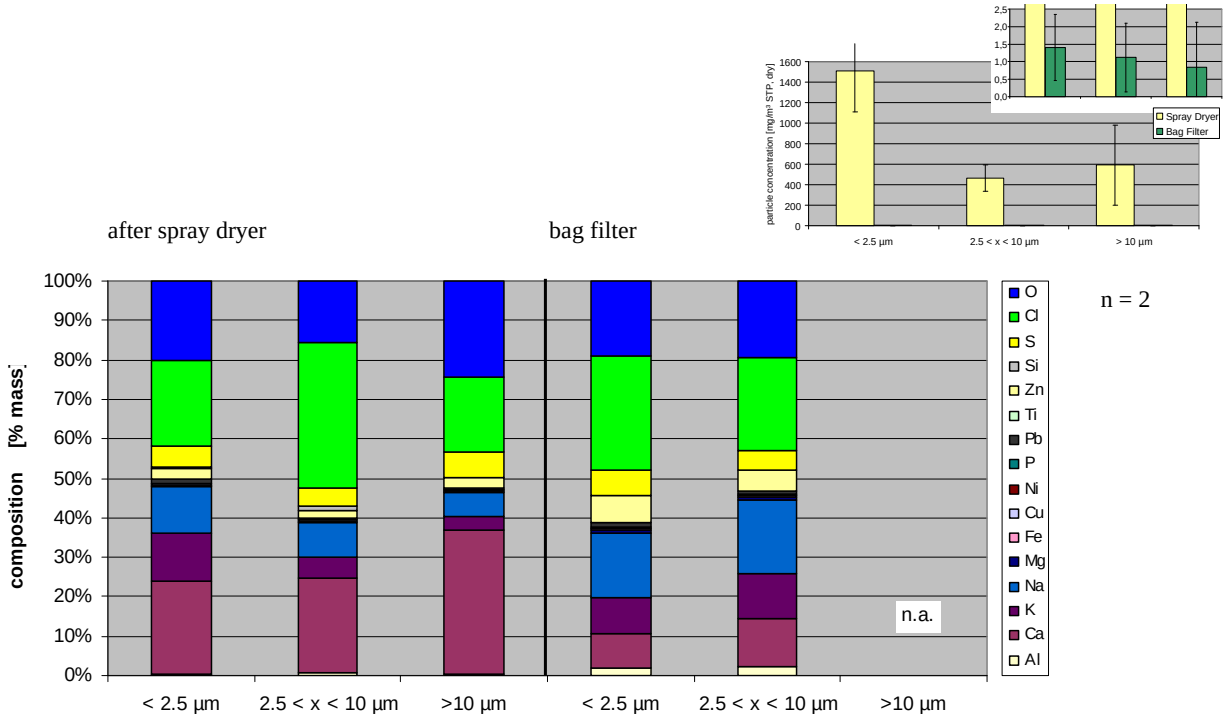


Figure 15: Change in particle composition in the bag filter (n.a. = to small sample to analyse)

Two stage scrubber

As mentioned, scrubbers are effective in fine dust removal. Therefore, the small amount of dust entering from the bag filter should be eliminated completely. Particles generated in the scrubber from sprayoff should have a composition similar to the scrubber slurry, i.e. contain both calcium chloride and calcium sulphate. Figure 16 shows the particles at the exit of the scrubber / demister / reheater combination consisting of calcium and sodium chlorides. Zinc as a tracer of combustion particles is eliminated completely.

The demister is a spray demister working with conditioned surface water from Main river which is recycled many times before leaving the demister. During operation it can absorb residual hydrogen chloride from the clean gas, leading to an increase in chloride content.

The particles composition lacking both sulphates and zinc leads to the clue, that the particles remaining in the flue gas probably are generated from the demister fluid. Unfortunately, the demister fluid cannot be sampled as long as the plant is running. Therefore it was not possible to compare the demister fluid composition to the residual dust composition.

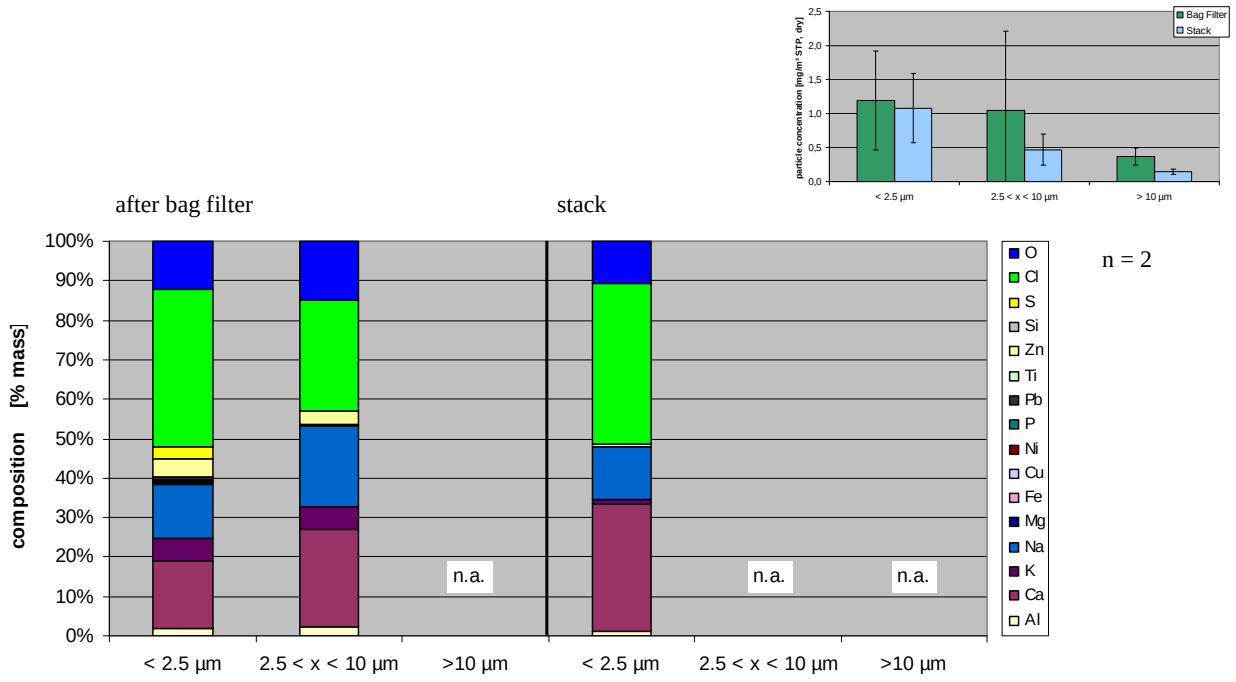


Figure 16: Composition of dust particles before and after the 2 stage scrubber (n.a. = to small sample to analyse)

4.3 Influence of soot blowing

The effect of soot blowing had been investigated during operation in the superheater section only. Action of soot blower # 3 situated between superheaters 5 and 6 caused a steep increase of dust concentration at the boiler exit. A peak concentration of 25000 mg/m³ was observed. As shown in Figure 17, coarse dust particles > 10 µm made up 90% of the total dust concentration, which led to overload on the >10 µm impactor plate. For weighing and subsequent analysis, loose particles on the impactor's 2nd stage and on the backup filter were added to the coarse dust fraction. The chemical analysis, however, suffered from that contamination, which led to increased calcium concentration in the dust particles collected on the filter (cf. Figure 18).

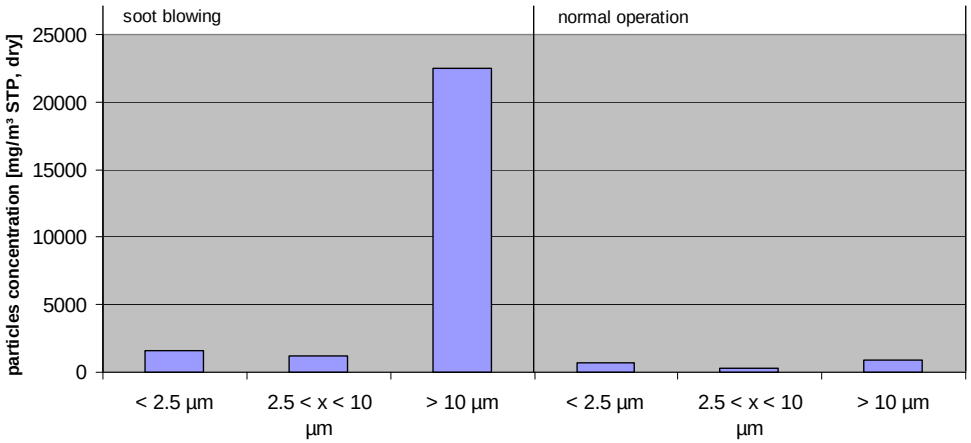


Figure 17: Effect of soot blowing on dust particle concentration and size distribution

The composition of the particles collected at the boiler exit (before the multiclone) and of those collected after the multiclone during soot blowing were quite similar to the composition of those particle fractions collected at normal operation of the boiler (Figure 19). As with these, the coarse dust particles (>10 µm) at the boiler exit mainly contained calcium, silicon and aluminium oxides together with a complex mixture of other elements. Most of the coarse dust being eliminated in the multiclone, the remaining particles > 10 µm had higher contents of sodium and potassium salts, resembling more the medium size particles (2.5 < x < 10 µm). As with the < 2.5 µm dust particles sampled at normal operation, the < 2.5 µm particles sampled during soot blowing seem to be contaminated from large dust particles. This is the only explanation, why they showed elevated calcium contents compared to the particles collected after the multiclone and compared to particles of that size sampled earlier in the 4th boiler pass and at the boiler exit.

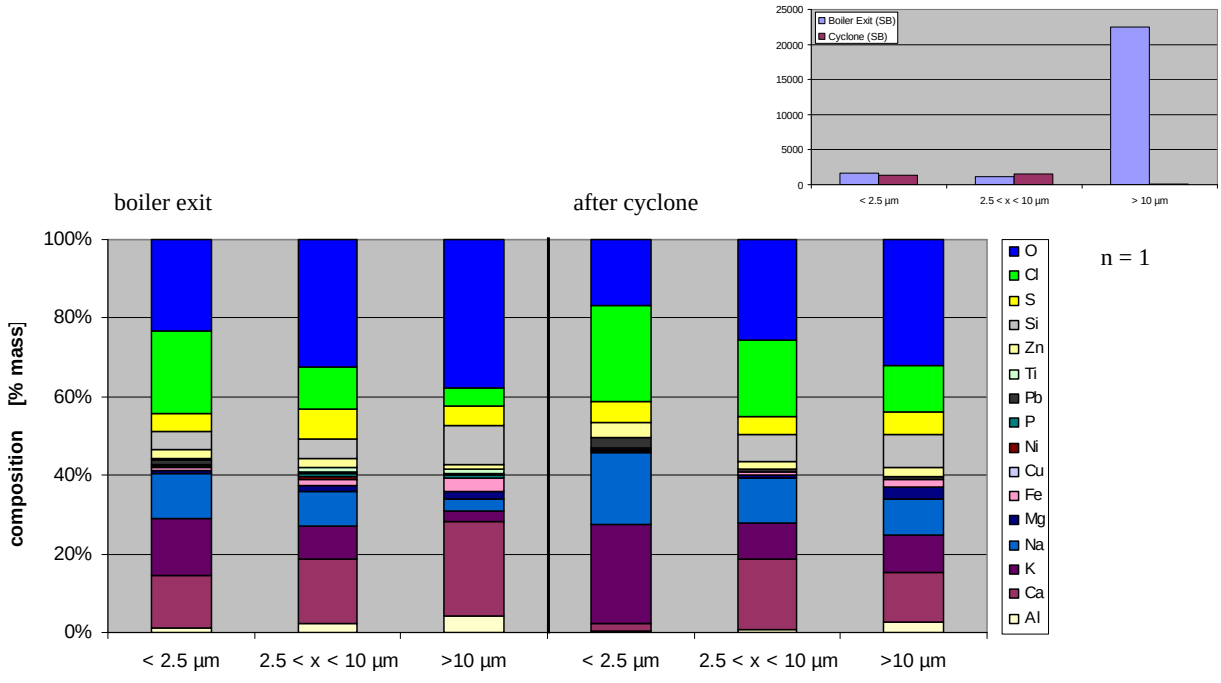


Figure 18: particle composition before and after the multiclone during soot blowing

Downstreams of the cyclone, the particles composition during soot blowing was almost the same as during normal operation (cf. Figure 19). As both the particles mass concentration downstream of the cyclone did not differ much between the operation modes and as most of the dust load after the spray dryer being next flue gas cleaning unit comes from the slurry evaporated, is was not necessary to study the influence of soot blowing on the following flue as cleaning steps.

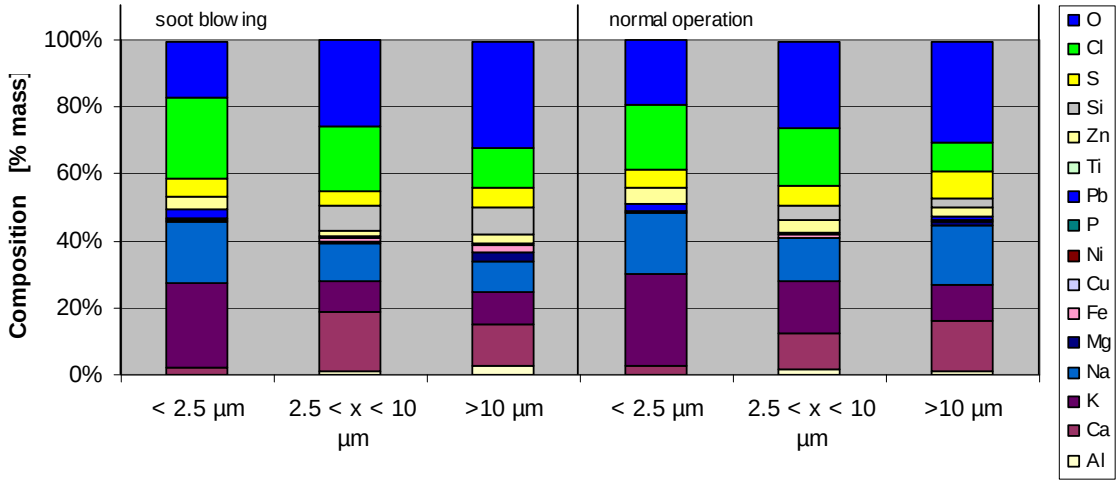


Figure 19: **Particle composition after the multiclone during soot blowing compared to the composition at normal operation**

4.4 Impact on the flue gas cleaning system

Considering pollution control, the 5 step flue gas cleaning system works at a very high level, yielding emission values below or far below all emission limits. With a multiclone, a bag filter and a washer, however, the system has three units consuming energy due to their pressure drop. This might be lowered by retrofitting to a “dry” flue gas cleaning system basing on calcium hydroxide or sodium bicarbonate. In this case only the bag filter would remain. However, flue gas cleaning efficiency and the capacity to handle peak concentrations are expected suffer from such a fundamental step. Therefore, this option is not considered further.

As long as the flue gas cleaning system is not retrofitted to a dry system, both the bag filter and the washer are indispensable and the focus is put on the multiclone.

4.4.1 Multiclone

Being the first unit of the flue gas cleaning system, the cyclone eliminates approximately 50% of the total dust load during normal operation and more than 85% of the dust occurring at soot blowing. After the multiclone, the flue gas is divided into two streams, about 6000 m³/h being recycled to the furnace and 36000 m³/h being cleaned further (normal operation conditions, full load). Elimination of the coarse dust is essential for the operation of the flue gas recycling system, because coarse dust would cause excessive erosion on the recycle gas blower and on the recycle gas duct. However, the coarse dust might be tolerated without problems in the flue gas cleaning units subsequent to the multiclone. The next flue gas cleaning unit is the spray dryer. The slurry being desiccated in the spray dyer forms new large dust particles, so particles entrained into the spray dryer probably should not be a problem for the bag filter. There is one mechanism, which might contribute to problems in the spray dryer: aggregates formed of coarse dust particles and slurry droplets might be large enough reach the spray dryer walls. Wet particles reaching the spray dryer walls stick there forming deposits which cause problems if these are growing too fast. Problems with deposits in the spray dryer have been observed even with the multiclone in operation when the slurry was not well dispersed into the gas stream.

At full load, the multiclone causes a pressure drop of 8 hPa. At 42000 m³/N (STP), an operation temperature of 210°C, 1000 hPa total pressure and 66% total efficiency of the fan this means a power consumption of 25 kW (13% of total power consumption of the induced draft fan (192 kW calculated from pressure drop and fan efficiency)). Compared to the he power required for operation of the bag filter (36 kW, pressure drop 14 hPa, 36000 m³/h STP), this is approximately 70%.
Hence, if it was possible to eliminate the multiclone, this would mean considerable energy savings.

If the flue gas recycle system has to be maintained, a part of the multiclone must remain in operation or be replaced by another dust elimination system in order to protect the flue gas recycle fan. The necessity of the flue gas recycle, however, should be checked thoroughly because elimination of the flue gas recycle could lower both the gas velocity in the boiler and the amount of salts entrained by approximately 20%. This might have a favourable effect on the boiler’s corrosion rates. If there would be no need for flue gas recycling, the multiclone might be eliminated totally.

4.4.2 Washer / Demister

In the 2 stage washer limestone meal is used as the neutralizing agent. In contrast to quicklime or hydrated lime, lime stone meal requires only a small amount of energy for preparation. Tests for minimizing the pressure drop along the washer have been run at GKS, but not within the scope of this task. As the washer performs well, there is no need for further optimization the performance.
Demisting the flue gas after the washer is essential for dust emission control. As there is a static demister at the scrubber exit, GKS considered to eliminate the water spray demister which should eliminate residual spray off. Efficiency of the wet demister can be deduced from the residual dust's chemical analysis:
The dust collected after washer, demister and reheating showed no traces of sulphates, which should occur if the demister was not operating well. With the lime stone meal added to the washer, calcium is introduced, therefore sprayoff from the washer could contain almost exclusively calcium salts. The amount of sodium entrained into the washer with the flue gas is negligible. Nevertheless, the dust collected after de washer / demister contains remarkable amounts of sodium salts. The demister operates on conditioned water from Main River which contains approximately 20 mg/l sodium and 100 mg/l calcium. Efficient elimination of washer sprayoff and generation of dust particles from the demister fluid explains the sodium content of the dust.
Obviously, in the demister there is an equilibrium between the exchange rate of the demister fluid and traces of residual HCl gas absorbed, resulting in quite high chlorides concentration in the residual dust. If the demister fluid was exchanged at a higher rate, it can be expected to attain even somewhat lower dust concentrations and lower particulate chlorides emission. However with dust emission rates well below 20% of the emission limits, there is no need for an improvement. Exchanging the washer spray off into the demister fluid spray off, gives additional safety in case of a heavy metals contamination of the washer, e.g. with mercury. This additional safety should be a reason not to eliminate the wet demister because especially mercury contamination is a permanent threat in incinerators [Gebhardt, 2005].

5 SUMMARY AND OUTLOOK

At GKS incineration plant particle elimination and particle size distributions in the flue gas cleaning system was evaluated. Three fractions of particle sizes (> 10 µm, 2.5< x < 10 µm, < 2.5 µm) were sampled on impactor substrates.

The results of chemical analysis allowed to determine the fate of particles coming from the boiler and gave insight into formation and elimination of particles formed within the flue gas cleaning plant.

The first step in the flue gas cleaning process is a multiclone, eliminating approximately 50% of total dust load. As typical for cyclones, mainly coarse dust particles are eliminated, leaving the fine dust particles (< 10 µm) with their high sodium and potassium chlorides content in the flue gas being recycled.
After the multiclone, lignite coke is injected contributing to the fine (< 10 µm) dust.

The next flue gas cleaning step is a spray dryer, which again contributes coarse dust particles. After the spray dryer, the dust composition is dominated by the particles formed in the dryer, mainly calcium chloride and calcium sulphate.

Apart of small residual concentrations, all dust particles are eliminated in the bag filter following the spray dryer. Although both fine and coarse dust particles are found after the bag filter, the chemical analysis showed a high similarity in the particles composition, indicating the coarse particles being formed by agglomeration of fine dust particles.

The 2 stage washer eliminates HCl, HF and sulphur oxides from the flue gas. It is equipped with a wet demister and a flue gas reheater. Particle concentration is not changed fundamentally in the washer / demister combination, but the results of chemical analysis showed the residual particles being formed in the wet demister. The latter obviously efficiently eliminates spray off from the washer which means enhanced security in case of a contamination of the washer.

As emission control works well, optimization of the flue gas cleaning system should focus on energy consumption. Considerable savings (13% of the induced draft fan energy consumption) would be possible if the multiclone could be eliminated. Total elimination of the multiclone would mean an end to the flue gas recycle system, so intensive testing is a prerequisite if elimination of the multiclone is considered.

The other flue gas cleaning steps should stay unchanged. Optimization of the pressure drop at the 2 stage washer was out of scope of the work presented.

6 LITERATURE

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