COMPARATIVE CHARACTERISATION OF HIGH TEMPERATURE AEROSOLS IN WASTE WOOD FIRED FIXED-BED AND FLUIDISED-BED COMBUSTION SYSTEMS

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ABSTRACT: The main differences in waste wood fired fixed-bed combustion systems and bubbling fluidised-bed combustion systems identified are lower temperature levels and higher concentrations of coarse fly ash particles, including bed material particles (quartz sand – SiO_2) entrained from the furnace, in fluidised-bed boilers compared to fixed-bed boilers. This is considerable important as aerosol forming processes are influenced by temperature levels as well as concentrations of coarse fly ash particles present in the flue gas. Firstly, lower temperature levels lead to an earlier condensation of aerosol forming elements on coarse fly ash particles and consequently reduce the aerosol concentration in BFB boilers. Furthermore, lower temperature levels reduce the sulphation of already formed KCl as well as the formation process of ZnO, decreasing the concentration of S and Zn in the aerosols formed in BFB combustion systems. Secondly, higher concentrations of coarse fly ash and bed material particles in the fluidised-bed combustion system compared to the fixed-bed combustion system provide additional particle surfaces on which aerosol forming elements can condense. Moreover, the high coarse fly ash concentrations cause increased reactions of S as well as Zn with coarse Ca-containing particles, consequently decreasing the aerosol concentrations emitted from BFB combustion systems.
Keywords: aerosol, waste wood, fixed bed, fluidized bed, chemical composition

1 INTRODUCTION

Fly ashes emitted from biomass combustion plants can generally be divided into coarse fly ashes (particles >1 µm) and aerosols (particles <1 µm). During the combustion of solid biomass fuels ash forming elements are involved in different processes of coarse fly ash and aerosol formation. Non-volatile compounds such as Si, Ca and Mg are engaged in ash fusion as well as coagulation processes. Easy volatile species such as K, Na, S, Cl, Zn and Pb are mostly released to the gas phase where they undergo gas phase reactions. As soon as the vapour pressure of a compound exceeds the saturation pressure by a high formation ratio or cooling the flue gas particle formation takes place (nucleation and condensation on the surface of existing particles). These formed particles coagulate with other aerosols or with coarse fly ashes as results of different relative particle motions due to Brown motion, turbulent eddies, thermophoresis and gravitational settling. The final particle size distribution of the aerosol mode results from particle formation by nucleation and growths of aerosol particles by condensation and by coagulation. [1, 2]

The major share of the coarse fly ash particles is precipitated in cyclones or filters while the major part of the aerosols is emitted with the flue gas at the boiler outlet and can only be precipitated in more advanced filter systems such as baghouse filters and electrostatic precipitators. Since the presence of coarse fly ashes influences the formation and behaviour of aerosols, the interactions between these two fractions have to be considered.

Detailed information about the different processes involved in aerosol formation has been already collected in several research projects. But for the first time this paper aims at the comparison and characterisation of aerosols formed during the combustion of waste wood in a fixed-bed combustion system and a bubbling fluidised-bed (BFB) combustion system. For aerosol characterisation, a new and innovative particle measurement device, a so called high temperature low-pressure impactor (HT-LPI), which can be applied in the hot furnace and boiler zones at temperatures of up to 1,100 °C, was applied.

1.1 Objectives

This paper aims at the evaluation, characterisation and comparison of aerosol forming processes in waste wood fired fixed-bed and BFB boilers. Therefore measurement campaigns at a grate-fired waste wood combustion plant as well as at a bubbling fluidised-bed waste wood combustion plant have been performed. The most important targets during the test runs were

- the application of the HT-LPI for aerosol measurements,
- the chemical composition of the aerosols sampled,
- the evaluation of the process data recorded during the campaigns and
- stable process conditions in order to achieve representative results.

1.2 Methods and materials

Test runs at a grate-fired waste wood combustion plant as well as at a BFB waste wood combustion plant have been performed. During the test runs the following samples were taken and measurements were performed:

- Determination of the particle size distribution (PSD) and concentration of aerosols in the flue gas in the hot furnace and the superheater section with 8-stage high temperature low-pressure impactor (HT-LPI).
- Determination of the particle size distribution (PSD) and concentration of aerosols in the flue gas at boiler outlet (downstream economiser) with 9-stage Berner-type low-pressure impactor (BLPI).
- Determination of the fly ash concentration in the flue gas at boiler outlet (downstream the

eocnomiser) using a sampling equipment according to VDI 2066.

- Determination of the chemical composition of aerosol and fly ash samples by wet chemical measures. Analyses method: pressurised multi-step digestion of the samples (HNO3/HF/H3BO3), element detection with ICP-MS or AAS [3, 4].
- Determination of the chemical composition of aerosols sampled on platinum foils by means of scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDX) [3, 4].
- Characterisation of the waste wood used (fuel samples were taken every 2 hours during the test runs and daily mixed samples were produced) by wet chemical analyses regarding the ash content as well as the concentrations of the most relevant elements (Si, Ca, Mg, K, Na, Zn, Pb, S, Cl, Al, Fe, Mn and P).
- To define the operation mode of the respective combustion plant during the test runs, plant operation data such as furnace temperatures, flue gas temperatures, the plant load as well as the O_2 and the CO-concentration in the flue gas were continuously measured, recorded and evaluated.
- Verification of the flue gas temperatures in the boilers measured and recorded by the plant operation system using a suction pyrometer according to IFRF and VDE.
- Characterisation of samples from the bottom ash and the boiler ash (boiler, superheater and economiser) taken during the test runs by wet chemical analyses regarding the concentrations of Si, Ca, Mg, K, Na, Zn, Pb, S, Cl, P, Fe, Al and Mn.
- Mass and element balances over the combustion plants based on these analyses data and on the operation data of the plants during the respective test runs in order to determine the behaviour and fluxes of ash and aerosol forming elements during combustion.

1.2.1 High temperature low-pressure impactor (HT-LPI)

For particle samples at high temperatures in the radiative and the convective path of a boiler a special high temperature low-pressure impactor (HT-LPI) was developed at the IPPT (Institute for Process and Particle Engineering) at the TU Graz, Austria, based on the common design of a Berner-type impactor. The HT-LPI (**Figure 1**) consists of 8 stages with a cut diameter between 0.09 µm and 2.60 µm defined by the volumetric flow rate through the impactor, the number and diameter of identical orifices and the distance between the orifice plate and the stagnation plate. Each stage consists of an orifice plate, a spacer ring and a stagnation plate. The volumetric flow is controlled by a critical orifice.

To facilitate an operation at temperatures of up to 1,100 °C special materials have been applied for the HT-LPI itself (heat resisting steel 15 X CrNiSi 25 20 and Inconell 600) as well as for the sampling foils (platinum) and the sealing (quartz). The HT-LPI is pre-heated in the furnace for a certain period of time (**Figure 2**), so consequently nucleation or condensation of vapors in the HT-LPI should not occur.
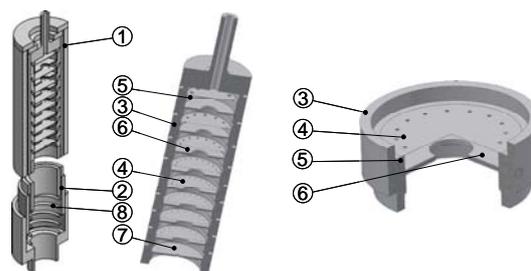

Figure 1: Basic design of the HT-LPI
Explanations: 1…outer casing, 2…inner casing, 3…shell, 4…orifice plate, 5…spacer ring, 6…stagnation plate, 7…critical orifice, 8 … spring

Figure 2: HT-LPI during and after measurement

The application of the HT-LPI made it possible to measure and characterise the aerosols formed at different locations in the boilers considering the concentration and the PSD of aerosols in the submicron range in different sections of the boilers and the chemical composition investigated by SEM/EDX analyses.

1.2.2 Ash balancing and concentration of coarse fly ash at the boiler inlet

The arising ash mass flow was calculated based on the ash content and the mass flow of the waste wood fired in the fixed-bed and the BFB combustion plant during the test runs. Furthermore, the bed material entrained from the BFB boiler was considered in the mass balance. The distribution of the ash to the ash fractions (bottom ash and fly ash in the boiler, superheater and economiser) was based on the experience of the plant operator. Based on wet chemical analyses and the ash mass flow of all ash fractions element balances have been performed identifying the distribution of major ash and aerosol forming elements in the ash fractions.

The concentrations of the coarse fly ash at the boiler inlet was calculated accumulating the coarse fly ash precipitated in the boiler (boiler, superheater, economiser) and the concentrations of the coarse fly ash measured at the boiler outlet.

1.2.3 Plant description

Measurement campaigns at a grate-fired waste wood combustion plant as well as at a BFB waste wood combustion plant have been performed. A strong focus

was put on stable process conditions during the test runs in order to achieve representative results.

In the grate-fired waste wood combustion plant (**Figure 3**) the inclined moving grate is fed with waste wood by a hydraulic stoker. The plant is equipped with a water-tube steam boiler (membrane wells), superheaters and an evaporator as well as an economiser. The flue gas is recirculated below and above the grate and cleaned by a double cyclone and a baghouse filter. SNCR is applied for NO_x reduction and a dry sorption system is applied for HCl, SO_x and PCDD/F-emission control. The nominal boiler capacity of the plant is 44 MW_{th} (steam parameters: 66 bar, 452°C).

During the test runs the combustion unit was operated at approximately 90% of the nominal boiler load. The waste wood used was of quality A1 to A4 according to German quality standards [5] and the chemical characterisation of the fuel is given in section 1.3. The maximum temperature level in the fixed-bed boiler was in the range of 1,100 °C as shown in section 5.
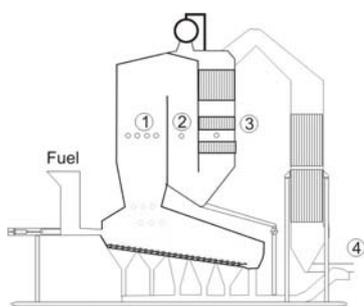

Figure 3: Scheme of the grate-fired waste wood combustion plant investigated
Explanations: HT-LPI measurements: 1st duct of the boiler – radiative section (1), 2nd duct of the boiler (2), downstream superheater 1 – convective section (3); BLPI and coarse fly ash measurement: downstream economizer (4)

The fuel feed in the bubbling fluidised-bed combustion plant (**Figure 4**) is a conveyor and the waste wood is brought into the boiler together with the recirculated flue gas. The bed material used in the bubbling fluidised-bed is quartz sand (SiO_2). The plant is equipped with a water-tube steam boiler (membrane wells), superheaters and an evaporator as well as an economiser. The flue gas is cleaned by a baghouse filter and a dry sorption system is applied for HCl and SO_x emission control. The nominal boiler capacity of the plant is 37.2 MW_{th} (steam parameters: 61 bar, 453°C).

During the test runs the combustion unit was operated at approximately 95% of the nominal boiler load. The waste wood used was of quality A1 to A3 according to German quality standards [5] and the chemical characterisation of the fuel is given in section 1.3. The maximum temperature level in the fluidised-bed boiler was in the range of about 900 °C as shown in section 5.
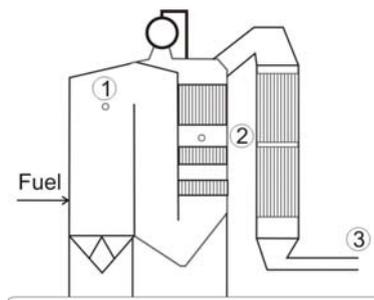

Figure 4: Scheme of the bubbling fluidised-bed waste wood combustion plant investigated
Explanations: HT-LPI measurements: 1st duct of the boiler – radiative section (1), downstream superheater 2 – convective section (2); BLPI and coarse fly ash measurement: downstream economizer (3)

1.2 Waste wood applied during the test runs

During the measurement campaigns fuel samples were taken every 2 hours and mixed to daily samples. The results of the fuel analyses are presented in **Table 1** and **Table 2**.

The waste wood fuels used in the grate-fired combustion plant as well as in the fluidised-bed combustion plant were homogenous over the duration of both test runs. The concentrations of major ash forming elements (Si, Ca, Mg, Al, Fe, P) were higher in the fuel used in the fixed-bed boiler (68,022 mg/kg (d.b.)) than the one in the fluidised-bed boiler (7,496 mg/kg (d.b.)) resulting in higher ash contents of the waste wood fired in the grate-fired combustion plant (16.4 wt% (d.b.) compared to 2.2 wt% (d.b.)). The concentrations of the most relevant aerosol forming elements (K, Na, Zn, Pb) were also higher in the fuel used in the fixed-bed boiler (6,095 mg/kg (d.b.) compared to 1,918 mg/kg (d.b.)).

Table 1: Characterisation of the waste wood used during the test runs at the grate-fired waste wood combustion plant
Explanations: d.b....dry base; Si+Ca+Mg+Al+Fe+P ...main ash forming elements; K+Na+Zn+Pb...aerosol forming elements; 2S/Cl...molar concentration ratio of 2S and Cl; K/Na...molar concentration ratio of K and Na

		average	standard deviation
Al	[mg/kg (d.b.)]	5,263	321
Ca	[mg/kg (d.b.)]	8,289	1,028
Cl	[mg/kg (d.b.)]	1,127	330
Fe	[mg/kg (d.b.)]	6,123	663
K	[mg/kg (d.b.)]	2,453	162
Mg	[mg/kg (d.b.)]	1,337	145
Mn	[mg/kg (d.b.)]	262	44
Na	[mg/kg (d.b.)]	2,707	495
P	[mg/kg (d.b.)]	354	32
Pb	[mg/kg (d.b.)]	141	22
S	[mg/kg (d.b.)]	1,427	252
Si	[mg/kg (d.b.)]	46,657	8,646
Zn	[mg/kg (d.b.)]	794	352
ash content	[wt% (d.b.)]	16.4	2.3
Si+Ca+Mg+Al+Fe+P	[mg/kg (d.b.)]	68,022	
K+Na+Zn+Pb	[mg/kg (d.b.)]	6,095	
2S/Cl	[mol/mol]	2.80	
K/Na	[mol/mol]	0.53	

Table 2: Characterisation of the waste wood used during the test runs at the bubbling fluidised-bed waste wood combustion plant

Explanations: d.b.…dry base; Si+Ca+Mg+Al+Fe+P …main ash forming elements; K+Na+Zn+Pb…aerosol forming elements; 2S/Cl…molar concentration ratio of 2S and Cl; K/Na…molar concentration ratio of K and Na

		average	standard deviation
Al	[mg/kg (d.b.)]	466	134
Ca	[mg/kg (d.b.)]	3,547	829
Cl	[mg/kg (d.b.)]	596	153
Fe	[mg/kg (d.b.)]	426	233
K	[mg/kg (d.b.)]	1,198	299
Mg	[mg/kg (d.b.)]	506	74
Mn	[mg/kg (d.b.)]	116	10
Na	[mg/kg (d.b.)]	542	93
P	[mg/kg (d.b.)]	168	46
Pb	[mg/kg (d.b.)]	56	32
S	[mg/kg (d.b.)]	490	63
Si	[mg/kg (d.b.)]	2,383	713
Zn	[mg/kg (d.b.)]	122	38
ash content	[wt% (d.b.)]	2.2	0.6
Si+Ca+Mg+Al+Fe+P	[mg/kg (d.b.)]	7,496	
K+Na+Zn+Pb	[mg/kg (d.b.)]	1,918	
2S/Cl	[mol/mol]	1.82	
K/Na	[mol/mol]	1.30	

2 ASH MASS FLOW DISTRIBUTION

In fixed-bed combustion systems the bottom ash is the dominating ash fraction with 60 – 90 % of the total ash mass flow [6]. About 10 – 40 % of the ashes is entrained from the fixed bed and can be found as boiler ash, cyclone ash and filter fly ash. In contrary in BFB units most of the ash is entrained from the fluidised bed and can be found as boiler ash, cyclone ash and filter ash. Additionally, in a BFB boiler bed material particles are entrained from the bed and are also part of the coarse fly ash found in the boiler, the cyclone and the filters.

The ash mass balance in the plants investigated follows the typical tendency (**Figure 4**). In the fixed-bed combustion system about 90 % of the ash could be found as bottom ash, 3 % as boiler+superheater+economiser fly ash and 7 % as fly ash emitted at the boiler outlet. In the BFB combustion system almost no bottom ash could be found while 21 % of the total ash was separated in the boiler, the superheater and the economiser. 79 % of the ashes left the economiser as fly ash emissions. The ratio of bed material particles, entrained from the bed, in the total ash mass flow was about 16 %. Almost 70 % of the bed material was precipitated with the boiler+ superheater+economiser ash, representing 54 % of the total mass flow there. At least 30 % of the bed material particles carried out was still present in the coarse fly ash in the flue gas at the boiler outlet.
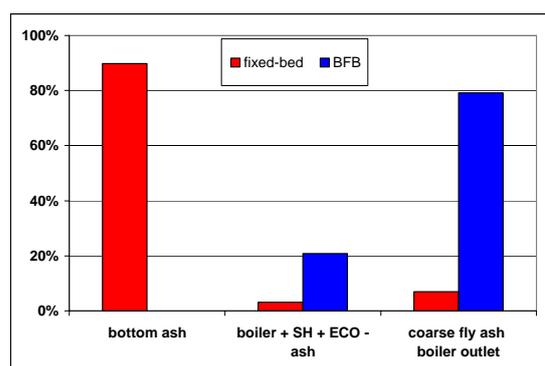

Figure 4: Ratio of the bottom ash, the boiler+SH+ECO ash and the coarse fly ash at the boiler outlet in the total ash mass flow in the fixed-bed and the BFB combustion system investigated

Explanations: fixed-bed…fixed-bed combustion system, BFB…BFB combustion system

3 CONCENTRATIONS OF COARSE FLY ASH PARTICLES IN DIFFERENT PLANT SECTIONS

As shown in **Figure 5**, the coarse fly ash concentrations at boiler inlet amounted to 1,550 mg/Nm³ for the fixed-bed combustion system and to 1,110 mg/Nm³ for the BFB unit. The concentrations of the fly ashes emitted at the boiler outlet decreased to 1,070 mg/Nm³ for the fixed-bed combustion plant and to 879 mg/Nm³ for the BFB unit.
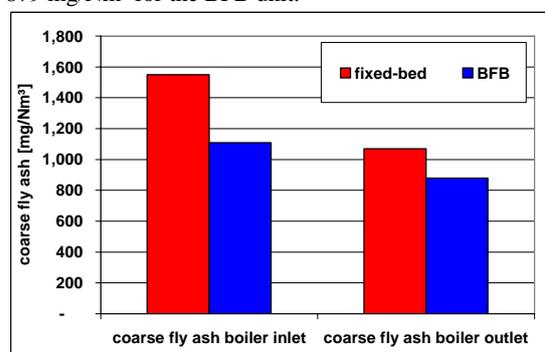

Figure 5: Trend of coarse fly ash concentrations at the boiler inlet and the boiler outlet in the waste wood fired fixed-bed and the BFB combustion plants investigated

Explanations: fixed-bed…fixed-bed combustion system, BFB…BFB combustion system; coarse fly ash concentration related to dry flue gas and 13 vol% O_2

However, when evaluating these results, the different ash contents of the fuels have to be considered, since with increasing ash contents also in the fixed-bed combustion plant the fly ash emissions increase [1]. Therefore the concentrations of coarse fly ash particles in the flue gas were related to the ash mass flow into the combustion systems in order to evaluate the results (**Figure 6**). For the BFB system the amount of bed material entrained from the bed had to be considered in the total ash mass flow.

In the BFB system the share of coarse fly ashes on the total ash was, as expected, significantly higher at the boiler inlet (1,000 g/kg ash compared to 102 g/kg ash) as well as at the boiler outlet (792 g/kg ash compared to 70 g/kg ash).
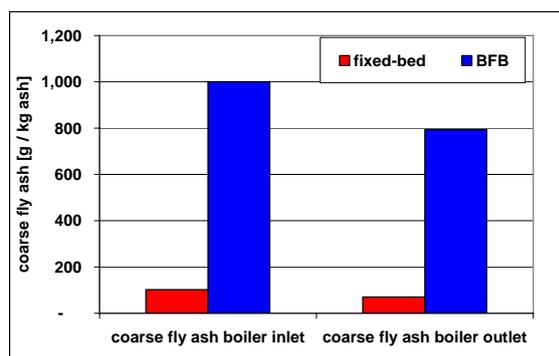
Figure 6: Trend of coarse fly ash concentration at the boiler inlet and the boiler outlet in the fixed-bed and the BFB combustion systems investigated related to ash mass flow

Explanations: fixed-bed…fixed-bed combustion system, BFB…BFB combustion system; coarse fly ash concentrations related to the ash mass flow; ash content: fixed-bed combustion system 16.4 wt% (d.b.), fluidised-bed combustion system 2.2 wt% (d.b.); entrained bed material from the fluidised bed considered in the calculations of the ash mass flow

5   TEMPERATURE PROFILE

In aerosol formation processes the temperature-profile of a combustion plant plays an important role. In **Figure 7** and **Figure 8** the temperature-profiles of the two combustion plants investigated are presented. The temperatures were taken from measured and recorded data by the plant operating system and averaged over the period of the test runs and, furthermore, the temperatures were verified using a suction pyrometer.
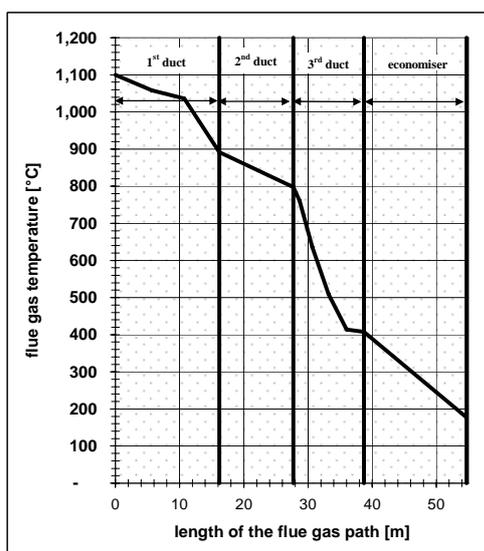

Figure 7: Trend of the flue gas temperature in the fixed-bed combustion plant investigated from the 1st duct to the boiler outlet

As **Figure 7** and **Figure 8** clearly show, the temperature level in BFB systems is generally lower. In the BFB unit the flue gas temperature decreases from about 890 °C at the end of the 1st duct over 673 °C upstream the superheater section to 450 °C upstream the economiser and finally 164 °C at the economiser outlet. While in the

fixed-bed combustion system the temperature decreases from about 1,100 °C at the end of the 1st duct over 800 °C at the inlet of the superheater section to 410 °C upstream the economiser and finally 177 °C at the economiser outlet.
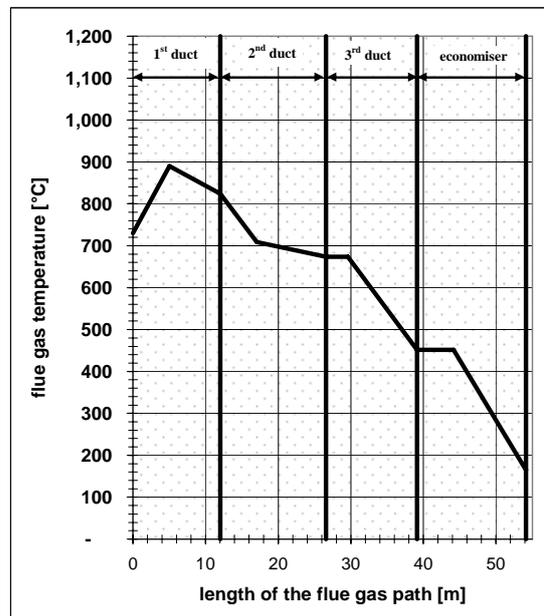

Figure 8: Trend of the flue gas temperature in the BFB combustion plant investigated from the 1st duct to the boiler outlet

5   AEROSOL FORMATION AND CHEMICAL COMPOSITION OF THE AEROSOLS

5.1 Aerosol concentration

In order to determine the concentration and PSD of aerosols HT-LPI measurements have been performed at the sampling points presented in **Figure 3** and **Figure 4**. Moreover, BLPI measurements were done downstream the economiser.

In **Figure 9** and **Figure 10** the aerosol concentrations measured in the radiative section (mean flue gas temperatures: fixed-bed: 889 °C, BFB: 826 °C) and the convective section (mean flue gas temperatures: fixed-bed 400 °C, BFB: 601 °C) of the boilers as well as at the boiler outlet (mean flue gas temperatures: fixed-bed: 182 °C, BFB: 163 °C) are presented. In the fixed-bed combustion system the aerosol concentration increases with decreasing flue gas temperatures from the radiative section (59.0 mg/Nm³) over the convective section (67.2 mg/Nm³) to the boiler outlet (87.4 mg/Nm³). The aerosol concentration in the BFB unit increases with decreasing flue gas temperatures from the 1st duct (12.6 mg/Nm³) over the superheater section (13.2 mg/Nm³) to the boiler outlet (29.0 mg/Nm³, all data related to dry flue gas and 13 vol% O_2).
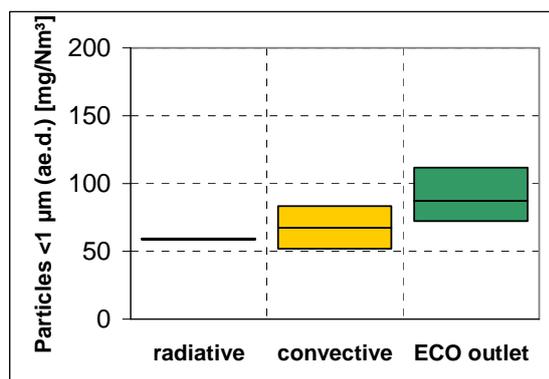
Figure 9: Aerosol concentrations in the radiative and the convective path as well as at boiler outlet in the fixed-bed combustion plant

Explanations: radiative and convective path measured by the HT-LPI; ECO outlet…at boiler outlet measured by the BLPI; average flue gas temperatures: radiative path: 889 °C; convective path: 400 °C; boiler outlet: 182 °C; ae.d…aerodynamic diameter; data related to dry flue gas and 13 vol% O_2
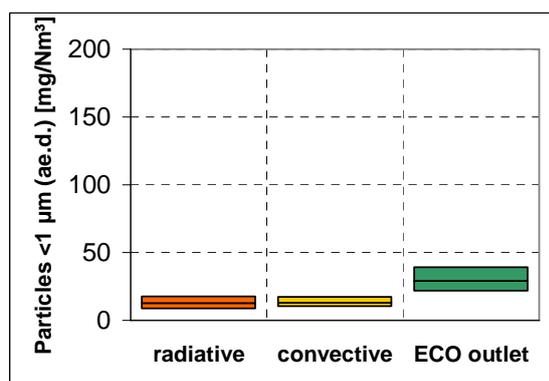

Figure 10: Aerosol concentrations in the radiative and the convective path as well as at boiler outlet in the BFB combustion plant

Explanations: radiative and convective path measured by the HT-LPI; ECO outlet…at boiler outlet measured by the BLPI; average flue gas temperatures: radiative path: 826 °C; convective path: 601 °C; boiler outlet: 163 °C; ae.d…aerodynamic diameter; data related to dry flue gas and 13 vol% O_2

In the BFB combustion plant the aerosol concentration in all sections is lower than in the fixed-bed combustion plant. Firstly, this is a result of the different compositions of the biomass fired in the fixed-bed boiler and the BFB boiler. The concentration of aerosol forming elements in the waste wood fired in the fixed-bed combustion system is higher (6,095 mg/kg (d.b.)) compared to the one used in the BFB combustion system (1,918 mg/kg (d.b.)). Secondly, the high concentrations of coarse fly ashes as well as the bed material particles (quartz sand – SiO_2) in the BFB combustion system provide additional surfaces for condensation of condensable ash forming elements and consequently particle formation by nucleation is partly suppressed. Moreover, higher concentrations of coarse fly ash particles also lead to increased reactions of aerosol forming elements with coarse particles. Furthermore, the lower temperature level in the BFB boiler leads to an earlier condensation of aerosol forming elements on these coarse fly ashes and bed material particles. That way aerosol forming elements are stronger embedded in other ash fractions as coarse fly ash and consequently the aerosol concentration in the BFB combustion system is lower than in the fixed-bed combustion system.

5.2 Chemical composition of the aerosols

The aerosols collected with the HT-LPI as well as the BLPI were investigated concerning their chemical composition by wet chemical and SEM/EDX analyses (**Figure 11** and **Figure 12**). The aim was to identify differences in the aerosol formation processes in fixed-bed and BFB systems.

In the 1st duct (mean flue gas temperature 889 °C) of the fixed-bed combustion system the aerosols mainly consist of K- and Na-sulphates as well as Zn-oxide and lower amounts of Si-oxide. With decreasing temperatures over the superheater (mean flue gas temperature 400 °C) and the economiser (mean flue gas temperature 182 °C) chlorine condensation starts, as it is confirmed by the higher Cl-concentrations in the particles sampled in these sections. Consequently, besides K- and Na-sulphates also –chlorides can be found. With increasing particle size the concentration of Si increases and also Ca and Mg can be found.
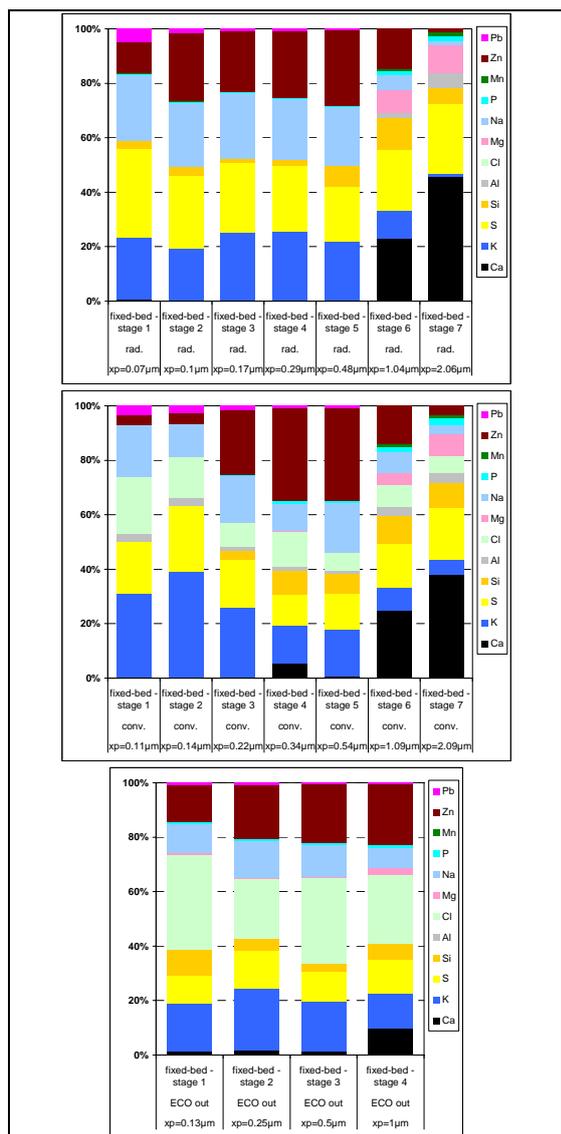
Figure 11: Chemical composition of the aerosols sampled with the HT-LPI (stages 1 to 7) as well as the BLPI (stages 1 to 4) at the waste wood fired fixed-bed combustion plant

Explanations: rad…radiative section (average flue gas temperature 889 °C); conv…convective section (average flue gas temperature 400 °C); ECO out…at boiler outlet (average flue gas temperature 182 °C); xp…cut diameter of the impactor stage; concentrations in [mol %]

Figure 12: Chemical composition of the aerosols sampled with the HT-LPI (stages 1 to 7) as well as the BLPI (stages 1 to 6) at the waste wood fired BFB combustion plant

Explanations: rad…radiative section (average flue gas temperature 826 °C); conv…convective section (average flue gas temperature 601 °C); ECO out…at boiler outlet (average flue gas temperature 163 °C); xp…cut diameter of the impactor stage; concentrations in [mol %]

The chemical composition of the aerosols sampled at the BFB boiler significantly differs from the fixed-bed system. In the 1st duct (mean flue gas temperature 826 °C) the aerosols mainly consist of K- und Na-chlorides as well as smaller amounts of –sulphates. Moreover, small amounts of Si-oxides and Ca- and Mg-oxides are found (stage 3 to 7). Again the Ca-, Mg- and Si-concentrations increase with increasing particle size which indicates that these particles originate partly from defragmentation processes. With decreasing temperatures downstream the superheater section (mean flue gas temperature 601 °C) and the boiler outlet (flue gas temperature 163 °C) the chemical composition of the aerosols does not change significantly.
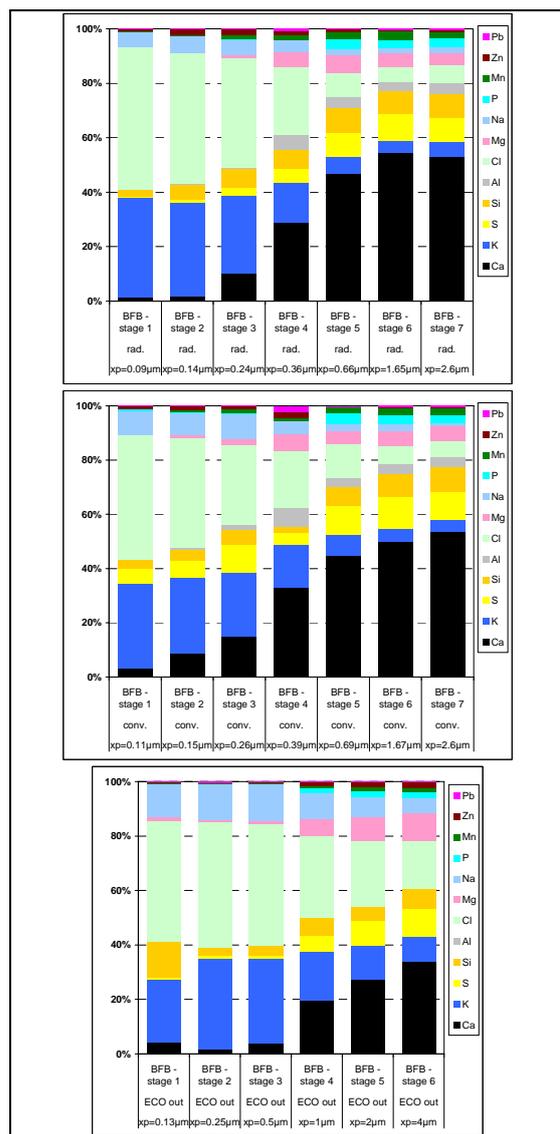
The most obvious difference between the fixed-bed combustion system and the BFB combustion system is the significantly lower amount of S in the aerosols sampled. First of all this is a result of the different biomass compositions. The higher 2S/Cl-ratio of the waste wood fired in the fixed-bed boiler (2.80) compared to the one used in the BFB boiler (1.82) contributes to a higher sulphation ratio. Furthermore, the higher concentration of Na-chlorides in the aerosols measured especially in the 1st duct in the fix-bed combustion system can be explained by the lower K/Na-ratio in the waste wood fired in the fixed-bed boiler (0.53) compared to the one used in the fluidised-bed boiler (1.30).

However, these arguments alone do not explain the extremely low S-concentration found in the aerosols in the BFB system. Also the typical characteristics of BFB

combustion plants, the high concentration of fly ashes and the presence of bed material as well as the comparably low combustion temperature have to be considered. The lower temperature levels in BFB systems retard the SO_2-SO_3-kinetics and consequently reduce the sulphation of already formed KCl. Furthermore, the lower temperature contributes an earlier condensation of S on coarse fly ash particles. Moreover, the higher concentrations of coarse fly ash particles as well as bed material particles in the BFB combustion plant (**Section 3**) compared to the fixed-bed boiler cause an increased reaction of the S with coarse Ca-containing particles.

Furthermore in the aerosols sampled in the BFB boiler almost no Zn was found. Besides the lower concentration of Zn in the waste wood fired in the BFB combustion system compared to the one used in the fixed-bed combustion system during the test runs, the forming of Zn-oxides has to be considered. Zn-oxide particles are formed at high temperatures directly after the flue gas leaves the fuel bed. The lower temperature levels in a BFB combustion system compared to the fixed-bed combustion system indicate that there is a lower release of Zn to the gas phase but a higher embedding in the coarse fly ash fraction.

The high content of chlorides in the aerosols of the fluidised-bed boiler will cause an increased corrosion risk in the superheater.

6 BEHAVIOUR OF CERTAIN ELEMENTS IN AEROSOL FORMING PROCESSES

Based on wet chemical and SEM/EDX analyses presented the behaviour of certain elements in aerosol forming processes was studied. The aim was to find out how elements and their compounds contribute in the formation of aerosols and to identify differences between a fixed-bed combustions system and a BFB combustion system.

6.1 Particle size distribution of the aerosols

The mean particle size distributions (PSD) of the aerosols sampled in the radiative and the convective section as well as at the boiler outlet of the fixed-bed and BFB combustion plant are presented in **Figure 13**. For the aerosols sampled in the fixed-bed boiler the peaks in the PSD in all boiler sections are identified at larger particle diameters than for the aerosols measured in the BFB boiler. The peak diameters in the fixed-bed combustion system increased from about 0.22 µm (ae.d.) in the radiative section over about 0.29 µm (ae.d.) in the convective section to 0.5 µm (ae.d.) at the boiler outlet. In the BFB combustion system the peak diameters were identified at a particle diameter of slightly above 0.11 µm (ae.d.) in the radiative section, of about 0.13 µm (ae.d.) in the convective section and of 0.18 µm (ae.d.) at the boiler outlet.
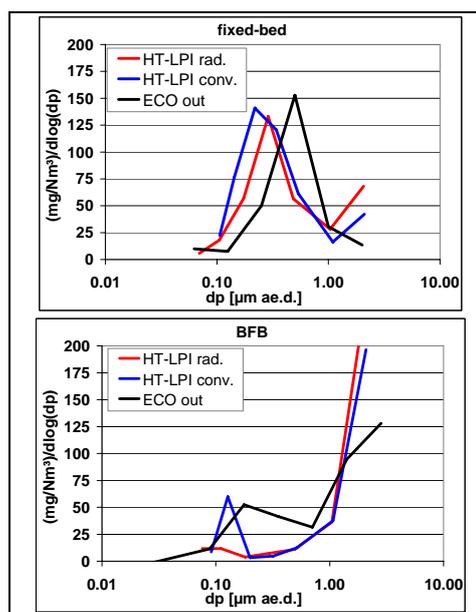

Figure 13: PSD of the aerosols in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system

Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [µm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

6.2 Particle size distribution of K in the aerosols

The concentrations of particle bound K in the different sections of the fixed-bed and the BFB combustion plant are presented in **Figure 14**. In the fixed-bed boiler the concentration of K is already very high in the radiative path of the boiler and increases only a bit in the convective path. Regarding the flue gas temperatures in the boiler sections and the concentration of K saturation of K-sulphates has already been exceeded before sampling point at the end of the 1st duct. Furthermore, almost no Cl was found in the aerosols in the radiative section. Hence, most of the K in the aerosols in the radiative section is bound in K-sulphates. In the convective section of the boiler and at the boiler outlet the concentrations of S decrease while the Cl-concentrations increase significantly. Consequently, K is also bound in chlorides.

In the BFB boiler the K-concentration increases significantly from the radiative to the convective path of the boiler and stays on the same level to the boiler outlet. With decreasing temperature levels from the radiative to the convective section of the boiler saturation of K-chlorides has been exceeded. Furthermore, regarding that almost no S was found in the aerosols sampled in the BFB combustion system and the PSD of Cl shows the same tendency most of the K in the aerosols in the BFB boiler is bound in K-chlorides.
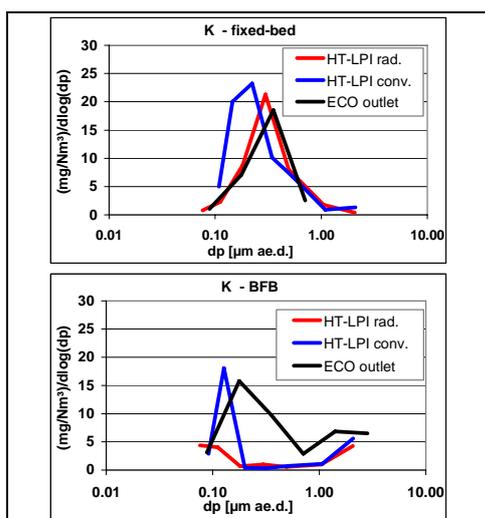
Figure 14: Concentrations of particle bound K in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [μm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

Figure 15: Concentrations of particle bound Na in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv…convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [μm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

6.3 Particle size distribution of Na in the aerosols

The concentrations of particle bound Na in the different sections of the fixed-bed and the BFB combustion plant are presented in **Figure 15**. In the fixed-bed boiler, where the total Na-concentration in the aerosols is higher than in the BFB boiler, the concentration of Na already reaches its maximum in the radiative path of the boiler and decreases a bit to the boiler outlet. Regarding the flue gas temperatures in the boiler sections and the saturation of possible chemical compounds most of the Na in the aerosols in the fixed-bed boiler seems to be bound in Na-sulphates. In the BFB boiler the Na-concentration in the radiative section is about 0 but increases in the convective path and to the boiler outlet. Hence, most of the Na in the aerosols in the BFB combustion system is bound in chlorides.
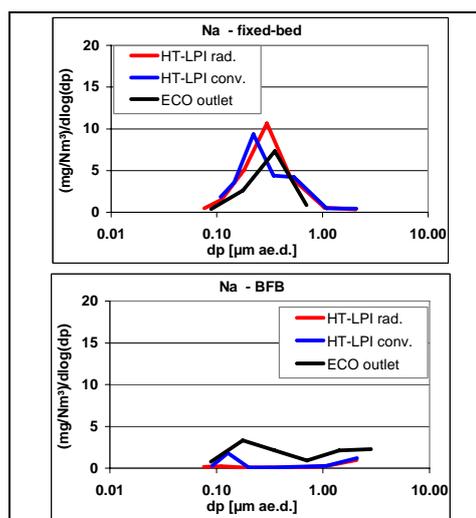
6.4 Particle size distribution of Ca in the aerosols

The concentrations of Ca in the aerosols measured in the fixed-bed and the BFB boiler are almost at the same level. There is almost no Ca in the small particle size classes (<1 μm) but a significant increase in larger classes. Regarding the PSD of S in the BFB combustion system the same trends can be observed confirming the conclusion of increased reactions of the S with coarse Ca-containing particles.
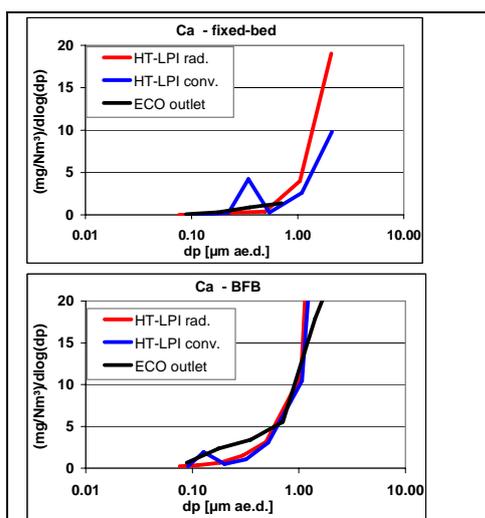
Figure 16: Concentrations of particle bound Ca in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [µm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

Figure 17: Concentrations of particle bound Cl in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [µm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

6.5 Particle size distribution of Cl in the aerosols

In the fixed-bed boiler the concentration of Cl increases steadily from the radiative section over the convective path to the boiler outlet, as already mentioned mostly bonded with K, while in the BFB boiler Cl already reaches its maximum concentration in the convective path (bonded with K and Na).

In both boilers investigated the total Cl-concentrations in the aerosols are nearly on the same level what is astonishing regarding the higher Cl-concentration in the fuel fired in the fixed-bed boiler (1,127 mg/kg (d.b.) compared to 596 mg/kg (d.b.)) and the higher total aerosol concentration emitted from the fixed-bed combustion system (87.4 mg/Nm³ compared to 29.0 mg/Nm³, all data related to dry flue gas and 13 vol% O_2). Firstly, the reason can be found in the lower 2S/Cl-ratio in the waste wood used during the test run at the BFB combustion system (BFB: 1.82; fixed-bed: 2.80). Consequently, more chlorides are formed, increasing the total concentration of Cl in the aerosol fraction. Secondly, the peak in the PSD of Cl in the aerosols sampled in the fixed-bed system is identified at a larger particle diameter than for the aerosols measured in the BFB boiler.
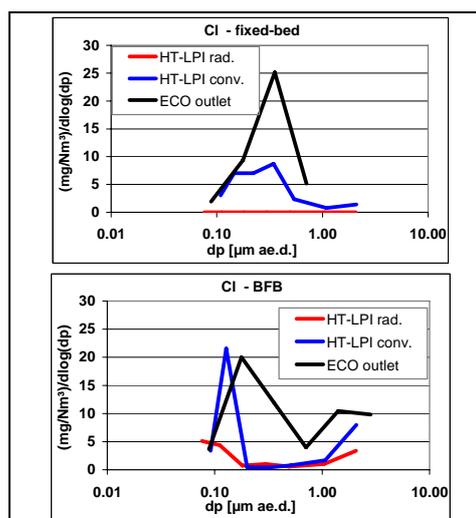
6.6 Particle size distribution of S in the aerosols

The concentration of S in the aerosols, measured in the fixed-bed boiler, already reaches its maximum in the radiative path of the boiler where, as mentioned above, K und Na are mostly bound as sulphates. Downstream the fixed-bed boiler the S-concentration decreases significantly. Potential reasons are deposit formation as well as an inhomogeneous waste wood fired. In the aerosols collected in the BFB boiler almost no S was found in small particle size classes over all sections of the boiler. Firstly, this is a result of the lower temperature levels in the BFB boiler that reduce the sulphation of already formed K-chloride. Secondly, the higher concentrations of coarse fly ash particles as well as bed material particles in the boiler lead to increased condensation on these particles as well as reactions of the S with coarse Ca-containing particles. Consequently, S is mainly embedded in other ash fractions as boiler+superheater+economiser fly ash and coarse fly ash as shown in section 7.
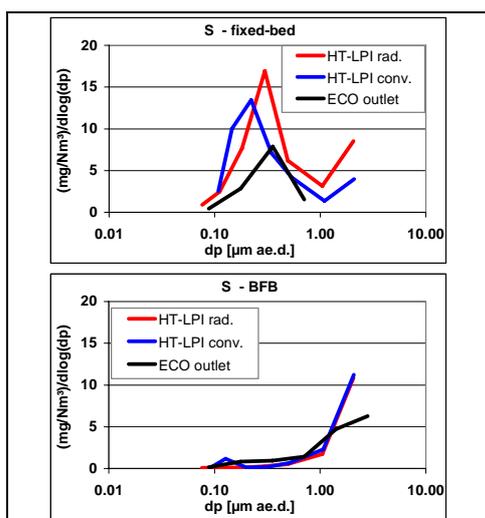
Figure 18: Concentrations of particle bound S in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [µm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

Figure 19: Concentrations of particle bound Zn in the flue gas in the radiative and the convective section as well as at boiler outlet in the fixed-bed combustion system and the BFB combustion system
Explanations: fixed-bed…fixed bed boiler; BFB…fluidised-bed boiler; HT-LPI measurement: rad…radiative section; conv… convective section; ECO outlet…at boiler outlet measured by the BLPI; dp [µm ae.d.]…aerodynamic diameter; all concentrations related to dry flue gas and 13 vol% O_2

6.7 Particle size distribution of Zn in the aerosols

In the fixed-bed boiler high concentrations of Zn were measured in the aerosols that were already formed in the radiative path of the boiler. The concentration of Zn, found as Zn-oxide, only increases a bit over the radiative section to the boiler outlet. In the aerosols collected in the BFB boiler nearly no Zn was found. Firstly, this is a result of the significantly higher Zn-concentration in the waste wood fired in the fixed-bed combustion system (949 mg/kg (d.b.) compared to 125 mg/kg (d.b.)). Regarding the distribution of Zn in the ash fractions, in the fixed-bed system 23.5 % of the Zn in the total ash was found in the aerosol fraction compared to the BFB unit where only 5.0 % of the Zn in the total ash was found in the aerosol fraction.

Secondly, ZnO particles are formed at high temperatures [1]. This formation of ZnO particles in a size range of some nanometers is assumed to take place directly after the flue gas leaves the fuel bed. The lower temperature levels in a BFB combustion system compared to the fixed-bed combustion system indicate that there is a lower release of Zn to the gas phase but a higher embedding in the coarse fly ash fraction.
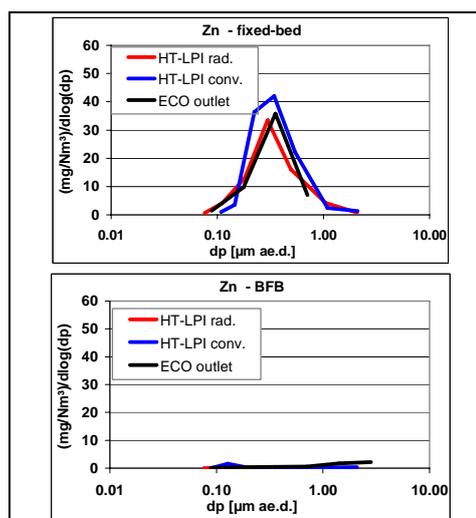
7 AEROSOL FORMATION PROCESSES IN FIXED-BED COMBUSTION SYSTEMS COMPARED TO FLUIDISED-BED COMBUSTION SYSTEMS

Based on the results presented aerosol formation processes in waste wood fired fixed-bed combustion systems and bubbling fluidised-bed combustion systems can now be evaluated and compared. However, it has to be taken into account that the concentration of aerosol forming elements in the waste wood fired in the fixed-bed boiler was about three times higher than in waste wood used in the BFB boiler. But it is generally agreed that the biomass composition has only minor influence on the release of aerosol forming elements to the gas phase as well as the aerosol forming processes as nucleation, condensation and coagulation.

7.1 Waste wood fired fixed-bed combustion system

In the fix-bed boiler the aerosol concentration in the radiative path (average flue gas temperature at sampling point 889 °C) was 59.0 mg/Nm³. The particles consist mainly of K- and Na-sulphates as well as Zn-oxides formed by nucleation and condensation and lower amounts of Si-oxides. The maximum temperature in the 1st duct of the fixed-bed combustion system is about 1,100 °C. As in the radiative section the flue gas temperature decreases, sulphur supersaturates and consequently, sulphates are formed as aerosols. Over the convective path (average flue gas temperature 400 °C) of the boiler the aerosol concentration increases up to 67.2 mg/Nm³ due to the decreasing flue gas temperature and resulting supersaturation of K- and Na-chlorides. To the boiler outlet (average flue gas temperature 182 °C) the aerosol concentration again increases up to 87.4 mg/Nm³ by the aerosol forming processes condensation and coagulation that also lead to particle

growth identified by the shift of the maximum in the particle size distributions of the elements to larger size classes.

7.2 Waste wood fired BFB combustion system

In the BFB combustion system smaller aerosol concentrations in all sections were determined. Firstly, this is a result of the different compositions of the biomass fired in the fixed-bed boiler and the BFB boiler. The concentration of aerosol forming elements in the waste wood fired in the fixed-bed combustion system is higher (6,095 mg/kg (d.b.)) compared to the one used in the BFB combustion system (1,918 mg/kg (d.b.)). The maximum temperature level in the 1st duct of the BFB boiler (890 °C) is much lower than in the fixed-bed boiler. At an average flue gas temperature of 826 °C at the end of the 1st duct an aerosol concentration of 12.6 mg/Nm³ was measured. The particles mainly consist of K- and partly Na-chlorides as well as smaller amounts of –sulphates and Ca-, Mg- and Si-oxides.

Over the convective path of the boiler (average flue gas temperature 601 °C) the aerosol concentration stays at about the same level (13.2 mg/Nm³) as well as the chemical composition of the aerosols remained unchanged. Firstly, between the radiative and the convective section the flue gas temperature only decreases down to about 600 °C (compared to about 400 ° in the fixed-bed boiler). Secondly, the aerosol concentration in the BFB boiler is lower than in the fixed-bed combustion system. Consequently, supersaturation does not lead to a significant increase of the aerosol concentration. Although the aerosol concentrations increase significantly to a level of 29.0 mg/Nm³ to the boiler outlet (flue gas temperature 163 °C) by condensation and coagulation that also lead to a particle growth, it is still much lower compared to the aerosol concentration measured in the fixed-bed boiler. The chemical compositions of the aerosols collected downstream the economiser are similar to the one after the convective path of the boiler. As almost no S is found in the aerosol fraction, the chemical composition remains unchanged over the sections of the boiler. Ca-, Mg- and Si-concentrations increase with increasing particle size in all sections of the BFB boiler, which indicates that these particles originate partly from defragmentation processes.

In opposite to the chemical composition of the aerosols measured in the fixed-bed boiler almost no sulphates were found in the aerosols collected in the BFB boiler. Firstly, the lower 2S/Cl-ratio in the waste wood fired in the BFB boiler (1.82) compared to the one used in the fixed-bed boiler (2.80) can be named as reason for the preferred formation of chlorides. Secondly, the lower temperature level in the boiler reduces the sulphation of already formed K-chlorides and furthermore contributes an earlier condensation of S on coarse fly ashes particles. The higher concentration of coarse fly ash particles and bed material particles in the boiler leads to increased condensation on these particles as well as reactions of the S with coarse Ca-containing particles and consequently a lower aerosol concentration in the BFB boiler.

Furthermore, also Zn is almost not present in the chemical composition of the aerosols contrary to the fixed-bed boiler where Zn-oxides represent a main component in the chemical composition of aerosols in all sections of the boiler. Besides the lower concentration of Zn in the waste wood fired in the BFB combustion system compared to the one used in the fixed-bed

combustion system during the test runs, this is a result of the lower temperature level in the BFB combustion system as well as the higher concentrations of coarse fly ash and bed material particles in the BFB boiler. The lower temperatures lead to a lower release of Zn to the gas phase and condensation on as well as reactions with coarse fly ash particles consequently lead to reduced aerosol concentrations in BFB combustion systems.

7.3 Distribution of ash forming elements in the different ash fractions

As mentioned above aerosol forming elements are significantly involved in reactions with coarse fly ash particles and bed material particles in BFB combustion systems. Consequently, comparing a fixed-bed and a BFB boiler these elements have to be found in higher concentrations in the ash fractions of BFB boilers than in the ones of fixed-bed boilers. Therefore, the bottom ash and the boiler+superheater+economiser fly ash were investigated concerning their chemical composition and compared with the chemical composition of coarse fly ash, aerosols and the gas phase at the boiler outlet. Furthermore, a mass balance has been performed (**Section 1.2.2**) considering especially the ash fractions in order to identify the embedding of relevant elements to the ash mass flows.

In the fixed-bed boiler (**Figure 19**) expectedly most of the elements can be found in the bottom ash in that the bottom ash represents 90 % of total ash mass flow. About 90 % of the major ash forming elements (Ca, Si, Mg, P, Fe and Al) can be found in the bottom ash, 1 to 4 % in the fly ash precipitated in the boiler, the superheater and the economiser and 6 to 9 % in the coarse fly ash at the boiler outlet. Almost the same tendency is determined for the aerosol forming elements K and Na, only the share of the aerosol fraction increases to 1 to 4 %. 67 % of Zn and Pb are found in the bottom ash, 20 to 23 % in the aerosol fraction at the boiler outlet, 9 to 11 % in the coarse fly ash at the boiler outlet and only about 1 % in the fly ash precipitated in the boiler, the superheater and the economiser. As expected most of S and Cl can be found in the gas phase at the boiler outlet (50 to 69 %), 5 to 15 % in the aerosol fraction at the boiler outlet and 14 to 15 % in the coarse fly ash at the boiler outlet. S is well embedded in the bottom ash (28 %).
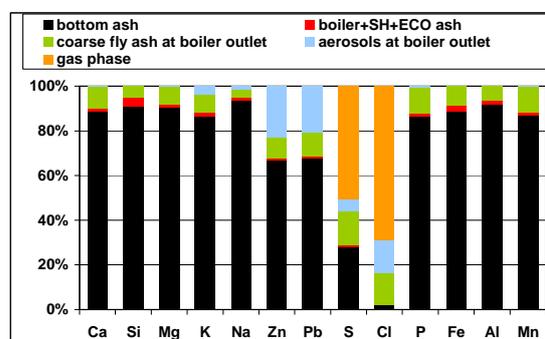

Figure 19: Involvement of elements in the ash mass fractions and the gas phase in the waste wood fired fixed-bed combustion system

Explanations: boiler+SH+ECO ash…fly ash precipitated in the boiler, the superheater section and the economiser; gas phase at the boiler outlet; allocation in [wt%]

In the BFB boiler (**Figure 20**) no bottom ash is

entrained from the boiler but as already mentioned above most of the ash is found as coarse fly ash at the boiler outlet (79 %) and as fly ash precipitated in the boiler, the superheater and the economiser (21 %).

85 to 94 % of the major ash forming elements (Ca, Mg, P, Fe and Al) can be found in the coarse fly ash at the boiler outlet, 3 to 15 % in the fly ash precipitated in the boiler, the superheater and the economiser and 1 to 3 % in the aerosol fraction at the boiler outlet. The high amount of Si separated in the boiler, the superheater and the economiser can be explained by the bed material (quartz sand – SiO_2) entrained from the fluidised bed. 5 to 14 % of the aerosol forming elements K, Na, Zn and Pb can be found in the aerosol fraction at the boiler, 78 to 89 % in the coarse fly ash at the boiler outlet and 3 to 14 % in the fly ash precipitated in the boiler, the superheater and the economiser. The share of S and Cl in the gas phase at the BFB boiler outlet is significantly lower than in the fixed-bed combustion system (42 % of Cl and only 9 % of S compared to 69 % of Cl and 50 % of S). 38 to 85 % can be found in the coarse fly ash at the boiler outlet, 4 to 20 % in the aerosol fraction at the boiler outlet and about 1 % in the fly ash precipitated in the boiler, the superheater and the economiser.

Once again, this is firstly a result of the high concentrations of coarse fly ash and bed material particles in the fluidised-bed boiler that lead to increased condensation on these particles as well as reactions of S and Zn with the particles. Secondly, the lower flue gas temperature level in the fluidised-bed boiler lead on the one hand to an earlier condensation of S on the coarse particles and on the other hand a reduced sulphation of already formed K-chlorides.
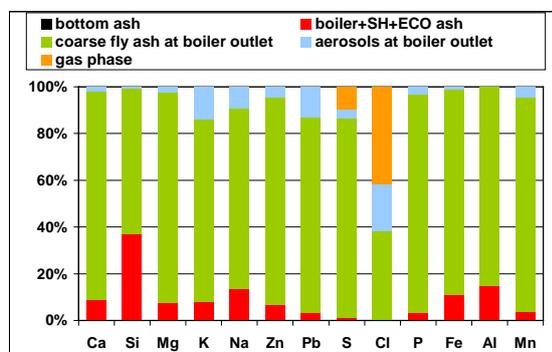

Figure 20: Involvement of elements in the ash mass fractions and the gas phase in the waste wood fired BFB combustion system
Explanations: boiler+SH+ECO ash…fly ash precipitated in the boiler, the superheater section and the economiser; gas phase at the boiler outlet; allocation in [wt%]

The embedded S was also detected on furnace fly ash particles by SEM/EDX analyses (**Figure 21**). At the border of a Si-particle (area 1) Ca and S were found supporting the conclusions already mentioned above.
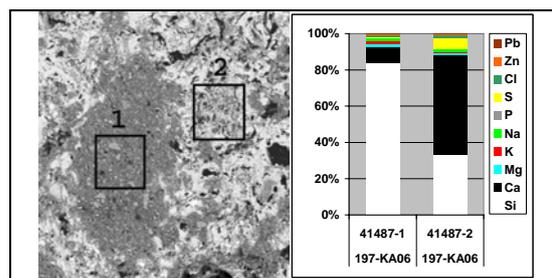

Figure 21: SEM/EDX analyses of a furnace fly ash particle (SiO2) and the agglomeration (especially Ca and S) deposited in the boiler
Explanations: furnace fly ash deposited in the boiler including the economiser

8 SUMMARY AND CONCLUSIONS

Based on data gained during test runs performed at a grate-fired waste wood combustion plant as well as at a bubbling fluidised-bed waste wood combustion plant it was found, that aerosol formation processes significantly differ between a fixed-bed combustion system and a bubbling fluidised-bed combustion system.

8.1 Differences of the plants and technology investigated

The concentration of the major ash forming elements (Si, Ca, Mg, Al, Fe, P) was higher in the waste wood fired in the fixed-bed boiler (68,022 mg/kg (d.b.)) than the one used in the BFB boiler (7,496 mg/kg (d.b.)). The concentration of aerosol forming elements was also higher in the fixed-bed boiler (6,095 mg/kg (d.b.)) than in the BFB boiler (1,918 mg/kg (d.b.)).

In the fixed-bed combustion system almost 90 % of the ash could be found as bottom ash, 3 % as fly ash precipitated in the boiler, the superheater and the economiser and 7 % as coarse fly ash at the boiler outlet. In the BFB combustion system 79 % of the total ash was found as coarse fly ash at the boiler outlet and 21 % as fly ash separated in the boiler, the superheater and the economiser. Consequently, the concentrations of coarse fly ash particles in the waste wood fired BFB combustion plant were much higher at the boiler inlet (BFB: 1,000 g/kg ash; fluidised-bed: 102 g/kg ash) as well as at the boiler outlet (BFB: 792 g/kg ash; fluidised-bed: 70 g/kg ash).

Generally, the temperature levels in fixed-bed combustion systems are higher than in BFB combustion systems. A maximum temperature level of about 1,100 °C was measured in the fixed-bed boiler compared to about 890 °C in the BFB boiler.

8.2 Differences in aerosol concentrations

In the BFB combustion plant the aerosol concentration in all sections is lower than in the fixed-bed combustion plant. In the fixed-bed combustion system the aerosol concentration increases with decreasing flue gas temperatures from the radiative section (59.0 mg/Nm³, mean flue gas temperature 889 °C) over the convective section (67.2 mg/Nm³, mean flue gas temperature 400 °C) to the boiler outlet (87.4 mg/Nm³, mean flue gas temperature 182 °C). The aerosol concentration in the BFB boiler increases with decreasing flue gas temperatures from the 1st duct (12.6 mg/Nm³, mean flue gas temperature 826 °C) over the superheater section (13.2 mg/Nm³, mean flue gas temperature

601 °C) to the boiler outlet (29.0 mg/Nm³, mean flue gas temperature 163 °C, all data related to dry flue gas and 13 vol% O_2).

8.3 Differences in the chemical composition of aerosols and formation pathways

In the 1st duct of the fix-bed boiler the aerosols mainly consist of K- and Na-sulphates as well as Zn-oxides formed by nucleation and condensation and lower amounts of Si-oxides. As in the radiative section the flue gas temperature decreases from the maximum boiler temperature, sulphur supersaturates and sulphates are formed as aerosols. Over the convective path due to decreasing flue gas temperatures and resulting supersaturation K- and Na-chlorides are formed. To the boiler outlet the aerosol forming processes condensation and coagulation, which also lead to particle growth, can be identified.

The chemical composition of the aerosols sampled at the BFB boiler significantly differs from the fixed-bed system. In the 1st duct the aerosols mainly consist of K- und Na-chlorides as well as smaller amounts of -sulphates and Ca, Mg and Si-oxides. Over the convective path of the boiler the chemical composition of the aerosols remains unchanged. Due to only a little flue gas temperature decrease as well as a lower aerosol concentration in the BFB boiler compared to the fixed-bed boiler supersaturation does not lead to a significant change in the chemical composition of the aerosols. The chemical compositions of the aerosols collected downstream the economiser are similar to the one after the convective path of the boiler. As almost no S is found in the aerosol fraction, the chemical composition remains unchanged over the sections of the boiler. Ca-, Mg- and Si-concentrations increase with increasing particle size in all sections of the BFB boiler, which indicates that these particles originate partly from defragmentation processes.

8.4 Conclusions

The main differences between a fixed-bed combustion system and a bubbling fluidised-bed combustion system are the lower temperature level in the BFB boiler as well as the higher concentration of coarse fly ash particles and entrained bed material particles in the boiler and at the boiler outlet. Aerosol formation processes are strongly influenced by these parameters. However, it has to be taken into account that the concentration of aerosol forming elements in the waste wood fired in the fixed-bed boiler was about three times higher than in waste wood used in the BFB boiler, it is generally agreed that the biomass composition has only minor influence on the release of aerosol forming elements to the gas phase as well as the aerosol forming processes as nucleation, condensation and coagulation.

Firstly, the lower temperature levels in the BFB system retard the SO_2-SO_3-kinetics and consequently reduce the sulphation of already formed KCl. Furthermore, the lower temperature contributes an earlier condensation of S on coarse fly ash particles. Consequently, the concentration of S in the aerosols and hence the attendance of S on aerosol formation processes is reduced significantly. However, S can be found for the most part in the coarse fly ash fraction.

Secondly, the lower temperature level in the BFB boiler reduces the formation of ZnO, which is formed at high temperatures directly after the flue gas leaves the fuel bed. Consequently, the concentration of Zn in the

aerosols decreases as the concentration in the coarse ash fraction increases

Furthermore, lower temperature levels also lead to an earlier condensation of aerosol forming elements on coarse fly ash particles again reducing aerosol formation.

This effect increases as the concentration of coarse fly ash as well as entrained bed material particles (quartz sand – SiO_2) provide larger additional surfaces for condensation of condensable ash and aerosol forming elements. Therefore, particle formation by nucleation is partly suppressed and aerosol concentration is reduced.

Moreover, higher concentrations of coarse fly ash particles also lead to increased reactions of aerosol forming elements as S and Zn with coarse Ca-containing particles. That way aerosol forming elements are stronger embedded in other ash fractions as coarse fly ash and consequently the aerosol concentration in the BFB combustion system is lower than in the fixed-bed combustion system.

Regarding aerosol forming processes in context with the chemical composition of waste wood fired in a combustion system the selection of the burning technology essentially influences the aerosol concentration as well as the chemical composition of the aerosols emitted off the boiler.

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10 ACKNOWLEDGMENTS