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ARTICLE *in* ENERGY & FUELS · OCTOBER 2002

Impact Factor: 2.79 · DOI: 10.1021/ef020076b

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Fly Ash Penetration through Electrostatic Precipitator and Flue Gas Condenser in a 6 MW Biomass Fired Boiler

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Received March 28, 2002

The effects of an electrostatic precipitator and a flue gas condenser on size resolved fly ash particle concentration and composition were studied in a 6 MW biomass combustion unit, fired with moist forest residue. The boiler was of moving grate type. The fly ash particles were sampled upstream and downstream of the electrostatic precipitator and flue gas condenser, respectively. Fine particle number size distributions were measured using an electric mobility spectrometer (SMPS) and coarse particle number size distributions were measured using a time-of-flight instrument (APS). The mass size distributions were measured using a multi-jet low pressure cascade impactor (DLPI). For chemical analyses of the impactor substrates particle induced X-ray emission analysis (PIXE) was used. After the flue gas passed the electrostatic precipitator (ESP), the fly ash particle concentration was reduced by approximately 96% by number and 83% by mass. After the particles passed the flue gas condenser, particle number concentration was only marginally altered, whereas the mass concentration was reduced by half. Both the ESP and the condenser showed, size dependent particle separation efficiency. The main elements ($Z > 12$) in the fine fly ash fraction were K, S, and Cl, whereas the main elements in the coarse fraction were Ca, K, S, and Cl. After passing the ESP the mass ratio of Ca decreased in the coarse fraction, while the ratios of K, S, and Cl increased, indicating transference of fly ash material from the fine to the coarse particle fraction. There was no significant difference in the elemental composition for any particle size fraction sampled upstream or downstream of the condenser.

Introduction

Small-scale biomass-fired district heating can be an economically and environmentally advantageous method to exploit locally produced biomass residues. In Sweden there is a growing number of small biomass-fired district heating plants (<10 MW, thermal) either in operation or in the planning phase. The majority of these boilers are of the grate type. The fuel is mainly locally produced biomass, like forest residues and waste from the wood industry. In addition, there are also a few boilers fired with processed biomass fuels such as pellets.

Grate combustion of biomass is generating small fly ash particles, which are transported with the flue gases in to the ambient atmosphere. These particles have a long residence time in the atmosphere and might be associated with adverse health effects due to their penetration and deposition in the lower respiratory tract and their enrichment of potentially toxic components.[1,2]

In Sweden, the particle emission requirement for small boilers (0.5−2 MW) is generally about 150 mg/Nm^3. This imposed restriction can generally be achieved by the use of cyclones. Slightly larger boilers often have more stringent particle emission requirements of approximately 50 mg/Nm^3 and are therefore equipped with an additional dust removal device, commonly a single field electrostatic precipitator. These boilers might also be equipped with a flue gas condenser, primarily for heat production. The condenser might also contribute to further fly ash removal.[3,4]

The efficiency of the dust removal equipment is in part determined by the fly ash particle size distribution and also the composition of the particles.[5−7] Circulating

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[†] Division of Bioenergy Technology.
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(1) Biedermann, F.; Obernberger, I. Fractionated Heavy Metal Separation in Biomass Combustion Plants−Possibilities, Technology, Experience and New Approaches. In *Proceedings of the 10th European Conference and Technology Exhibition*, Biomass for Energy and Industry, June 8−11, 1998, Würzburg, Germany; C. A. R. M. E. N: Rimpar, Germany, 1998; pp 1340−1343.
(2) Lighty, J.; Veranth, J.; Sarofim, A. *J. Air Waste Manage. Assoc.* **2000**, *50*, 1565−1618.
(3) Neuenschwander, P.; Good, J.; Nussbaumer, Th. Combustion Efficiency in Biomass Furnaces with Flue Gas Condensation. In *Proceedings of the 10th European Conference and Technology Exhibition*, Biomass for Energy and Industry, June 8−11, 1998, Würzburg, Germany; C. A. R. M. E. N: Rimpar, Germany, 1998; pp 1340−1343.
(4) Jakobsen, H. H. *Flue Gas Condensation of Chips Fired Boiler at Gørding District Heating Plant*; Danish Institute of Forest Technology: Copenhagen, 1991.
(5) Durham, M. D.; Rugg, D. E.; Rhudy, R. G.; Puschaver, E. J. *J. Air Waste Manage. Assoc.* **1990**, *40*, 112−124.

10.1021/ef020076b CCC: $22.00
Published on Web 10/03/2002

fluidized bed (CFB) combustion of wood has been shown to produce a fly ash mass size distribution with at least two distinct modes.[8] During biomass combustion the coarse fly ash particles (>1 μm) are formed mainly from refractory ash components such as Ca, Mg, and Si, whereas fine particles in the sub-micometer range, are formed mainly from constituents that are vaporized in the combustion process e.g. alkali, sulfates and chlorides.[9−11] In the CFB, a major part of the refractory ash will be re-circulated in the furnace until deposited in the bed material or fragmented to a size small enough to pass the process cyclone. Consequently, in CFB combustion of wood, the fly ash mass will generally be dominated by the coarse fraction, upstream of the particle emission control device.

Grate combustion of wood was also shown to produce a bimodal fly ash mass size distribution, but in this case the fly ash is usually dominated by the fine mode.[12−14] In a grate boiler the refractory ash will not be fragmented as effectively as in a CFB, but will to a larger extent be transported out of the boiler as bottom ash. Consequently, the coarse fraction of fly ash will generally be lower in a grate boiler than in a CFB. Also the concentration of the coarse particle fraction during grate combustion of wood was shown to depend on the operating parameters, in particular the load.[13,14] The mechanism for the formation of coarse particles, as well as the mechanisms determining the load dependency, are not fully understood.

The total mass collection efficiency for electrostatic precipitators (ESP) is generally very high and can easily exceed 99%.[6] However, field measurements have shown that there is a "penetration window" in the submicrometer size range where the collection efficiency can be as low as 70−80%.[15−17] Electrostatic precipitators are widely used for particulate control and extensive research has been done on several aspects of this, such as improving the collection efficiency for small particles.[18,19]

Since the efficiency for particle removal by the ESP is size dependent, the total fly ash will be enriched in components more abundant in the size fractions that are less effectively separated. This particle size dependent penetration through the ESP during pulverized coal combustion has been investigated.[20−22]

Furthermore, composition dependent selective penetration, where particles of the same size but with different composition, show different degrees of penetration, was also reported.[6,7] In one study a South African coal was used to fire a power plant equipped with a highly efficient ESP.[7] Particles in the 1−5 μm range were collected upstream and downstream of the ESP and were analyzed by means of a proton microprobe. Particles of the same size could be classified into several groups with different elemental composition. Particles classified into the two major groups (group 1 and group 2) together constituted approximately 80% of the particles, both at the inlet and the outlet of the ESP. Before the ESP, group 1 was the most abundant (63% for group 1 and 16% for group 2), while at the outlet group 1 was depleted (34%) and group 2 was enhanced (44%). This composition dependent selective penetration was assumed to be related to the elemental composition and the affect this had on the electrical properties of the fly ash particles, such as resistivity, which can influence the electrostatic precipitation process.

In a previous study, the hygroscopic growth of fine particles from a 1 MW boiler fired with moist forest residue was observed using a hygroscopic tandem differential mobility analyzer.[23] The results indicate a similar growth factor for particles of the same size.[23] The authors interpretation was, that particles of a given size had identical or at least similar chemical composition. However, SEM images and EDX analyses of filter samples from wood combustion indicates that, for the coarse fraction, particles of the same size might have different compositions.[13]

There is little information on particle separation in flue gas condensers. However, wet scrubbers have been frequently used for particle separation. This is especially the case when there are additional gaseous elements to be removed, such as SO_2 and HCl, for which the removal efficiency of the scrubber is very high. Typically, the particle-laden gas flows upward and liquid droplets are sprayed into the gas. The droplets will settle to the bottom and collide with particles on their way up. The most important particle removal mechanisms are diffusion, interception, inertial impaction, and gravitational settling.[24] In condensation scrubbers, an additional mechanism is involved in order to enhance the deposition rate of small particles. When the hot aerosol saturated with water vapor is cooled, some of the vapor

(6) Zhuang, Y.; Kim, Y. J.; Lee, T. G.; Biswas, P. *J. Electrostat.* **2000**, *48*, 245−260.
(7) Cereda, E.; Marcazzan, B. G. M.; Pedretti, M.; Grime, G. W.; Baldacci, A. *J. Aerosol Sci.* **1996**, *27*, 607−619.
(8) Valmari, T.; Kauppinen, E. I.; Kurkela, J.; Jokiniemi, J. K.; Sfiris, G.; Revitzer, H. *J. Aerosol Sci.* **1998**, *29*, 445−459.
(9) Christensen, K. A.; Stenholm, M.; Livbjerg, H. *J. Aerosol Sci.* **1998**, *29*, 421−444.
(10) Valmari, T.; Lind, T. M.; Kauppinen, E. I. *Energy Fuels* **1999**, *13*, 379−389
(11) Pagels, J.; Gudmundsson, A.; Bohgard, M.; Strand, M.; Lillieblad, L.; Sanati, M.; Swietlicki, E. In *Proceedings of the American Association for Aerosol Research*, AAAR 2000−19th Annual Conference, Nov 6−10, 2000, St. Louis; p 148, 4PJ6,
(12) Hasler, P.; Nussbaumer, T. Particle Size Distribution of the Fly Ash from Biomass Combustion. In *Proceedings of the 10th European Conference and Technology Exhibition*, Biomass for Energy and Industry, June 8−11, 1998, Würzburg, Germany; C. A. R. M. E. N.: Rimpar, Germany, 1998; pp 1330−1333.
(13) Obernberger, I.; Brunner, T.; Jöller, M. Characterisation and Formation of Aerosol and Fly-Ashes from Fixed-Bed Biomass Combustion. In *Seminar on Aerosols from Biomass Combustion*; International Energy Agency and the Swiss Federal Office of Energy 27, Swiss Federal Institute of Technology, ETH: Zurich, Switzerland, June 2001; p 6.
(14) Pagels, J.; Strand, M.; Gudmundsson, A.; Szpila, A.; Swietlicki, E.; Sanati, M.; Bohgard, M. *J. Aerosol Sci.* **2001**, *32* (Suppl. 1), 973−974.
(15) Mohr, M.; Ylätalo, S.; Klippel, N.; Kauppinen, E. I.; Riccius, O.; Burtscher, H. *Aerosol Sci. Technol* **1996**, *24*, 191−204.
(16) Ylätalo, S. I.; Hautanen J. *Aerosol Sci. Technol.* **1998**, *29*, 17−30.
(17) McCain, J. D.; Gooch, J. P.; Smith, W. B. *J. Air Pollut. Control Assoc.* **1976**, *25*, 117−121.
(18) Biswas, P.; Wu, C. Y. *Air Waste Manage. Assoc.* **1998**, *48*, 113−127.
(19) Zukeran, A.; Looy, P. C.; Berezin, A. A.; Chang, J. S.; Ito, T. *J. Aerosol Sci.* **1997**, *28*, 281−282.
(20) Brooks, Rizeq, R. G.; Hansell, D. W.; Seeker, W. R. *Fuel Process. Technol.* **1994**, *39*, 219−236.
(21) Lind, T.; Kauppinen, E. I.; Valmari, T.; Klippel, N.; Mauritzson, C. *J. Aerosol Sci.* **1995**, *26* (Suppl. 1), 13−14.
(22) Helble, J. J. *Fuel Process. Technol.* **2000**, *63*, 125−147.
(23) Rissler, J.; Swietlicki, E.; Zhou, J.; Pagels, J.; Gudmundsson, A.; Szpila, A.; Bohgard, M.; Strand, M.; Sanati, M. *J. Aerosol Sci.* **2001**, *32* (Suppl. 1), 29.
(24) Kim, H. T.; Jung, C. H.; Oh, S. N.; Lee, K. W. *Environ. Eng. Sci.* **2001**, *18*, 125−136.

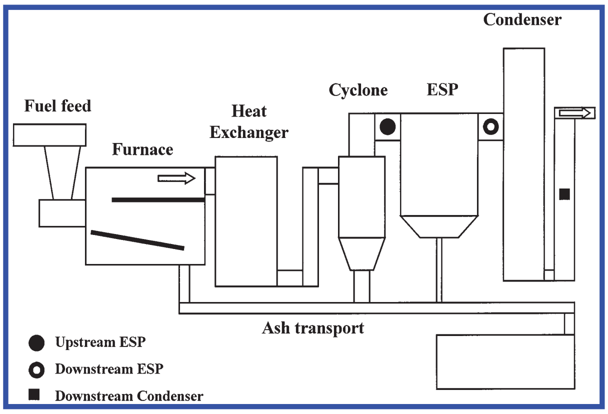

Figure 1. Scheme of the moving grate boiler equipped with multicyclone, electrostatic precipitator (ESP) and flue gas condenser. Samples were collected downstream from the cyclone, downstream from the ESP, and downstream from the condenser.

will condense on the particles, which will be more susceptible to separation by inertial impaction.[25]

Flue gas condensers are generally not optimized for particle separation, since the equipment is designed for heat recovery purposes. However, it is known that the flue gas condenser also can reduce the particle concentration and that particles >10 μm can be separated almost completely.[3]

Information on the penetration of fly ash through ESP and condenser will improve the possibilities to predict particle emissions from biomass fired boilers. It might also promote better understanding of particle behavior and particle separation mechanisms in different kinds of emission control devises. In this work particle size distribution and particle composition were studied at different positions in a 6 MW district heating boiler fired with moist forest residue and equipped with an ESP and a flue gas condenser. The investigation is focused on the effect of particle size and particle composition on ESP and condenser penetration.

Experimental Section

Process Description. The measurements were carried out in a commercial 6 MW moving grate boiler equipped with a multi-cyclone and a single field electrostatic precipitator (ESP) for particle removal and a flue gas condenser for heat recovery (Figure 1). Measurements were carried out over a 2 day period. During the whole period, the boiler was fired with the same kind of moist forest residue and all operating parameters were kept close to constant.

The ESP was designed for a minimum particle removal of 94%, by mass. In the ESP gas molecules are ionized by corona discharge at the discharge electrode. The particles are charged by the ionized gas molecules and transported in the electrical field to the grounded collection plates. The separated dust is removed from the collection plates by rapping at a set frequency. The dust is then removed from the ESP by a conveying screw. To facilitate the transport to the conveying screw, vibrators are connected to the outside of the ash hopper.

The boiler was equipped with a flue gas condenser in order to increase the capacity of the plant by recovering more heat from the flue gas. By decreasing the flue gas temperature below the dew point, the latent heat from the condensing water vapor can also be recovered. The thermal output from the flue

(25) Johannessen, T.; Christensen, J. A.; Simonsen, O.; Livbjerg, H. *Chem. Eng. Sci.* **1997**, *52*, 2541−2556.

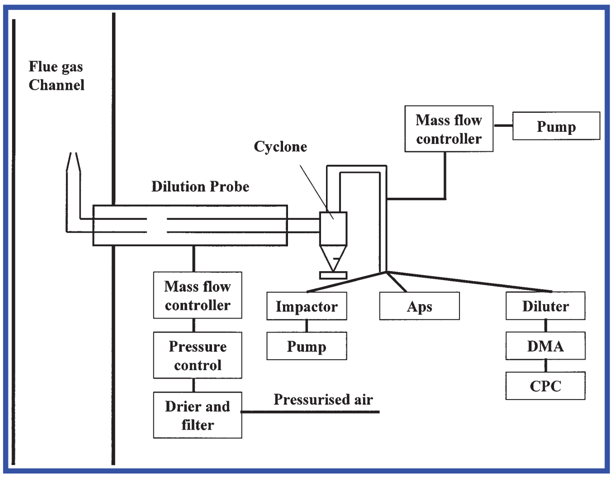

Figure 2. Particle sampling system and size distribution measurement system including low-pressure cascade impactor, APS instrument, and SMPS instrument (DMA + CPC).

gas condenser depends on the content of water vapor in the incoming flue gas and to what temperature that the gas can be cooled. In the flue gas condenser the gas passes downward through cooled vertical tubes at a velocity of 20−30 m/s in order to ensure a high heat transfer coefficient between the flue gas and the pipe surface. The inside walls of the tubes are rinsed by flushing water from the top.

The flue gas temperature downstream of the multicyclone and the ESP was approximately 180 °C. Downstream of the condenser the gas temperature was 55−60 °C. During the measurements the boiler load fluctuated between 4.5 and 5.0 MW. The output of the flue gas condenser was close to 1 MW during all measurements.

Particle Sampling. The aerosol particles were sampled downstream of the multicyclone, ESP and flue gas condenser. Measurements downstream of the multicyclone (i.e., upstream of the ESP) were carried out on the first day and measurements at the other two positions were carried out on the second day. Sampling was carried out for about 3 h at each sampling position. The aerosol was sampled isokinetically using a dilution probe (Figure 2).

To decrease the gas temperature, particle concentration and relative humidity, the flue gas was diluted (1:20) using particle-free dry compressed air. The flow of air for dilution and the outlet excess flow were controlled using mass flow controllers. To control the dilution rate, first the flow of dry air to the inlet was set. Then the flow of concentrated flue gas into the probe was set to zero. This was accomplished by slowly increasing the outlet excess flow to the point where the APS instrument started to indicate particles in the sampling line. The dilution rate was then set by further increasing the outlet excess flow through the mass flow controller. After the dilution-probe the gas passed a precyclone with a d_{50} of 8 μm, to avoid clogging in the downstream equipment.

Fly Ash Characterization. Number size distributions of coarse particles (aerodynamic diameter 0.8−6 μm) were studied using a time-of-flight instrument (TSI, APS 3320). The APS provides real-time high-resolution measurements of particle concentration and size distribution in the coarse particle range.

An electric mobility spectrometer (TSI SMPS 3934) was used for studying the number size distribution of fine particles, with a mobility equivalent diameter of 0.02−0.6 μm. To reduce the concentration to within the optimal range of the SMPS, the flue gas was further diluted by 1:10 before entering the instrument. The dilution was accomplished using an ejector diluter (VKL Palas GmbH).

The mass size distributions were measured with a Dekati 13 stage multi-jet low-pressure cascade impactor (DLPI). The DLPI classifies the aerosol particles into 13 size fractions (d_{50}

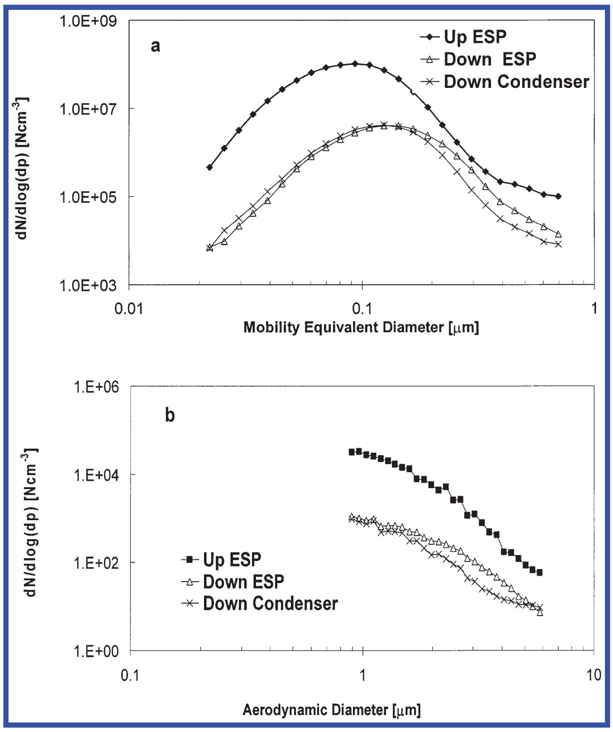

Figure 3. Particle number distribution upstream of the ESP, downstream from the ESP, and downstream from the condenser. (a) Results fine particles by SMPS. (b) Results coarse particles by APS.

0.030−10.33 μm) according to their aerodynamic diameter by means of inertial impaction on to substrates. The sampled mass was determined by weighing the substrates before and after sampling. Greased nuclepore polycarbonate filters were used as impactor substrates. One measurement was carried out at each sampling position. Impactor stage 12 ($d_{50} = 6.80$ μm) and 13 ($d_{50} = 10.37$ μm) are not presented in this report since they were affected by the particle losses in the sampling system. The substrates were greased with Apiezon low vacuum grease and were baked at least 5 h at 125 °C to avoid mass loss during sampling. All gravimetric analysis of the substrates were carried out at a relative humidity below 30% in order to avoid the influence of water adsorbed to the substrate or to the collected material.

For elemental analyses of impactor samples, particle induced X-ray emission (PIXE) was used. Approximately 30 elements were analyzed. Since PIXE is not suitable for elements with atomic number less than 13, ash components, such as Na and Mg, were not analyzed. The accuracy of the PIXE analysis is typically within 10%.

All number and mass concentrations are given for dry gas and 13% CO_2.

Results and Discussion

ESP Fly Ash Penetration. Time average, particle number size distributions and number concentrations, as measured upstream and downstream of the ESP are given in Figure 3 and in Table 1. Figure 3a shows the fine fraction measured by the SMPS. The corresponding coarse fraction measured by the APS is shown in Figure 3b.

Number distribution, upstream of the ESP, was close to unimodal, with an average geometric mean diameter (GMD) of 0.088 μm. The average fine particle number concentration was 4.4 × 10^7 particles Ncm^{-3}. The average coarse particle number concentration was 8.7 × 10^3 particles Ncm^{-3}. When measured downstream of the ESP, the GMD increased to 0.127 and the number concentration was reduced by approximately 96% for both the fine and the coarse fractions.

Table 1. Number Concentrations, Geometric Mean Diameters, and Number Collection Efficiencies Meassured with SMPS and APS Instruments

	$d_p < 0.6$ μm	$0.8 < d_{ae} < 6$ μm	total
	Number Concentrated (1/Nm^3 [a])		
upstream of the ESP	4.42×10^7	8.69×10^3	4.42×10^7
downstream from the ESP	1.79×10^6	3.34×10^2	1.79×10^6
downstream from the condenser	1.72×10^6	2.45×10^2	1.72×10^6
	Geometric Mean Diameter (μm)		
upstream of the ESP	0.088		
downstream from the ESP	0.127		
downstream from the condenser	0.117		
	Number Collection Efficiency (%)		
ESP	96.0	96.1	96.0
condenser	3.9	26.6	3.9

[a] 1 Nm^3 = 1 m^3 at 0 °C, 1 bar and 13% CO_2.

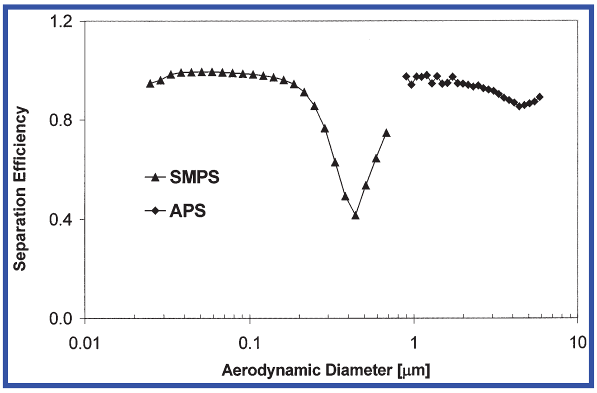

Figure 4. ESP separation efficiency given by SMPS and APS. SMPS data recalculated for aerodynamic diameter.

Particle size dependent collection efficiency for the ESP is given in Figure 4.

To display the SMPS and APS results in the same figure, aerodynamic diameters were calculated from the mobility equivalent diameter given by the SMPS data. The mobility equivalent diameter could be approximated to the Stokes diameter, if spherical particles are assumed. The aerodynamic diameter d_{ae} can be calculated from the Stokes diameter d_p by

$$d_{ae} = d_p \sqrt{\frac{\rho_p C_c(d_p)}{C_c(d_{ae})}}$$

where ρ_p is the particle density and C_c is the Cunningham slip correction factor. The aerodynamic diameter was calculated iteratively from Stokes diameter and the result is plotted in Figure 5. From the composition analysis, the particle density ρ_p was estimated to be 2 g/cm^3.

As illustrated in Figure 4, there is a penetration window for the particle diameter interval between 0.1 and 1 μm. This is consistent with previously reported

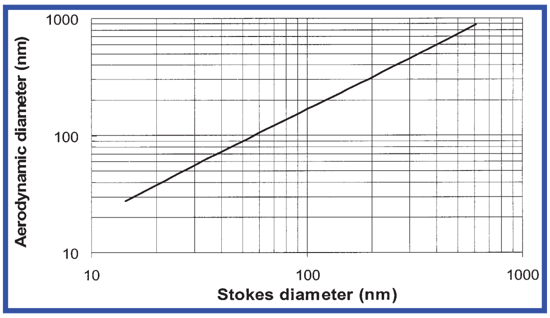

Figure 5. Mobility equivalent diameter (Stokes diameter) plotted versus aerodynamic diameter, assuming spherical particles and particle density of 2 g/cm^3.

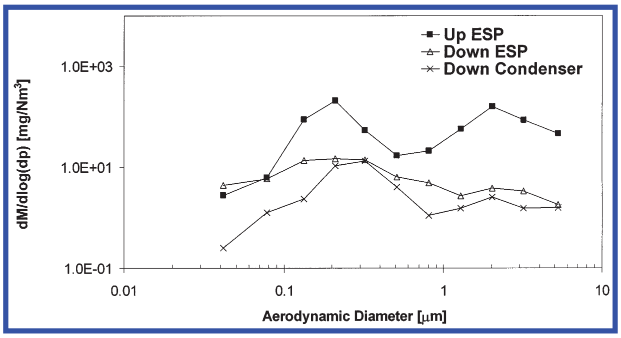

Figure 6. Particle mass size distributions measured with DLPI.

experimental as well as theoretical results.[16,17,26] The very low collection efficiency of about 0.5 in the 0.3−0.6 μm size range is striking. This observation may result from particles in this size range penetrating the ESP, but also from agglomerates formed during the precipitation process. The mass concentration of particles in the 0.3−0.6 μm size range was in the order of a magnitude lower than the mass concentration of the slightly smaller particles. Possibly a fraction of the smaller particles form agglomerates by some mechanism in the ESP. Some of these agglomerates might then be transported out of the ESP with the flue gas, boosting the already high penetration in the submicrometer range.

Particle mass size distributions and mass concentrations were measured with the DLPI. The results from upstream and downstream of the ESP are given by Figure 6 and Table 2.

The mass size distribution is bimodal with a fine particle mode around 0.2 μm and a coarse particle mode around 2 μm. The mass concentration upstream of the ESP was 134 mg/Nm^3 with 57% of the particle mass in the fine mode. Downstream of the ESP the particle mass was reduced by approximately 83% in the fine mode and 95% in the coarse mode. The lower mass collection efficiency (83%) compared to the number collection efficiency (95%) in the fine mode is consistent with the offset of the GMD caused by the low collection efficiency of the ESP in the 0.1−1 μm range. However, as seen from Figure 6 the mass of the finest particles (<0.2 μm) downstream from the ESP seems to be very high and inconsistent with the SMPS results.

Condenser Fly Ash Penetration. Particle number size distribution during measurements downstream from the flue gas condenser were very similar to the results from upstream of the condenser (Figure 3a,b), indicating a very low separation efficiency of the flue gas condenser. According to SMPS data, fine particle number concentration was reduced from 1.8 × 10^6 to 1.7 × 10^6 particles/Ncm^3 (Table 1). This represents a change that is within the error of the measurement method used. Also in the coarse particle size range, number concentration was only slightly reduced from 330 to 250 particles/Ncm^3. There was a slight shift in the particle geometric mean diameter from 0.127 μm to 0.117 μm (Table 1).

According to impactor measurements, the mass concentration of fine particles was reduced by about 50% (Table 2) downstream of the condenser.

The collection efficiency of a gravitational wet scrubber has been investigated.[24] The authors found that the overall collection efficiency was represented by a U-shaped curve, with a minimum around 1 μm. The geometric mean diameter of aerosol particles was affected in two regions, the diffusion-dominant submicron region, and the impaction-dominant supermicron region. An increase in GMD was observed for the diffusion-dominant region, and a corresponding decrease for the impaction-dominant region. The design of the gravitational wet scrubber is however different from the flue gas condenser. In the scrubber a large amount of small droplets are sprayed into the gas, providing a large surface area for submicron particle deposition, by diffusion, and coarse particle deposition, by impaction. In the condenser the droplet surface area is much lower, since there is no spraying of water into the gas. The residence time in the condenser is also very short, providing little time for particle transport by diffusion. The most probable deposition mechanism in the condenser is inertial impaction of coarse particles to the walls of the condenser, due to the turbulence caused by the high velocity of the gas.

The high relative humidity prevailing in the condenser might enhance the deposition by inertial impaction due to particle growth by condensation of water.

Table 2. Mass Concentration and Particle Collection Efficiencies Measured with Impactor and Calculated from SMPS and APS Data[a]

	d_{ae} < 0.8 μm	0.8 < d_{ae} < 6 μm	total
Mass Concentration Impactor (mg/Nm^3 [a])			
upstream of the ESP	76.3	58.5	134.9
downstream from the ESP	13.2	2.6	15.8
downstream from the condenser	6.3	1.8	8.2
Mass Concentration SMPS and APS (mg/Nm^3 [a])			
upstream of the ESP	62.2	9.7	86.3
downstream from the ESP	8.3	0.60	10.1
downstream from the condenser	5.5	0.34	6.5
Mass Collection Efficiency Impactor (%)			
ESP	82.6	95.6	88.3
condenser	52.3	30.7	51.9
Mass Collection Efficiency SMPS and APS (%)			
ESP	86.7	92.5	88.3
condenser	33.7	44.4	35.6

[a] 1 Nm^3 = 1 m^3 at 0 °C, 1 bar and 13% CO_2.

(26) Kim, S. H.; Park, H. S. *J. Electrostat.* **2001**, *50*, 177−190.

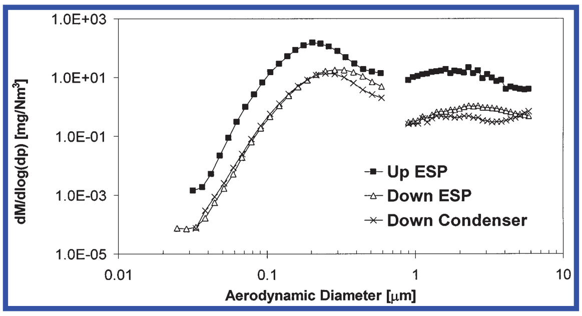

Figure 7. Calculated mass distributions from SMPS and APS data, assuming spherical particles and a density of 2 g/cm^3.

Since the fly ash particles contain hygroscopic components i.e., salts, water vapor will deposit on the particles even at subsaturated conditions. The hygroscopic growth of fine particles from a 1 MW boiler of similar design and using similar fuel was verified by using H-TDMA.[23] The obtained results showed relatively high hygroscopic properties of the particles with a growth factor of 1.6–1.9, at 90% relative humidity. The H-TDMA instrument does not allow for investigation of the coarse fraction. However, since the coarse particles also contain a substantial fraction of elements (K, S, and Cl) that are likely to be present as hydrophilic compounds, the coarse particles also might grow by condensation of water vapor at subsaturated conditions.

Calculated Mass Distribution and Mass Concentration. To compare the number and mass size distributions, particle mass distributions were calculated from SMPS and APS data. Spherical particles with a density of 2 g/cm^3 were assumed. Calculated mass size distributions from all measurement points are given in Figure 7.

The calculated mass concentrations are given in Table 2. There is a fairly good compliance between the calculated mass and the measured mass from the impactor substrates in the fine particle range, indicating that the assumed particle density is accurate. However, the mass concentrations in the coarse range, calculated from the APS data, accounted for only about 20% of the measured amount at all three measurement positions. This lack of agreement might be due to experimental/instrumental inaccuracies. It might also be due to inaccuracies in the assumed coarse particle density and morphology. The assumed particle density and spherical shape might be a good approximation for fine particles formed by condensation of volatilized species, while coarse particles might be more correctly represented as porous structures and/or aggregates with a low effective density. Neglecting the slip correction factor, the mass of a particle with an aerodynamic diameter d_{ae} is given by

$$m = \frac{\pi d_{ae}^3}{6 \cdot \sqrt{\rho_e}}$$

where ρ_e is the effective density of the particle. In the impactor, as well as in the APS, particles are classified according to their aerodynamic diameter. As the particle mass is approximately inversely proportional to the square root of the effective density, large and hollow aggregates will be classified as particles with a small aerodynamic diameter and a large mass. If a coarse

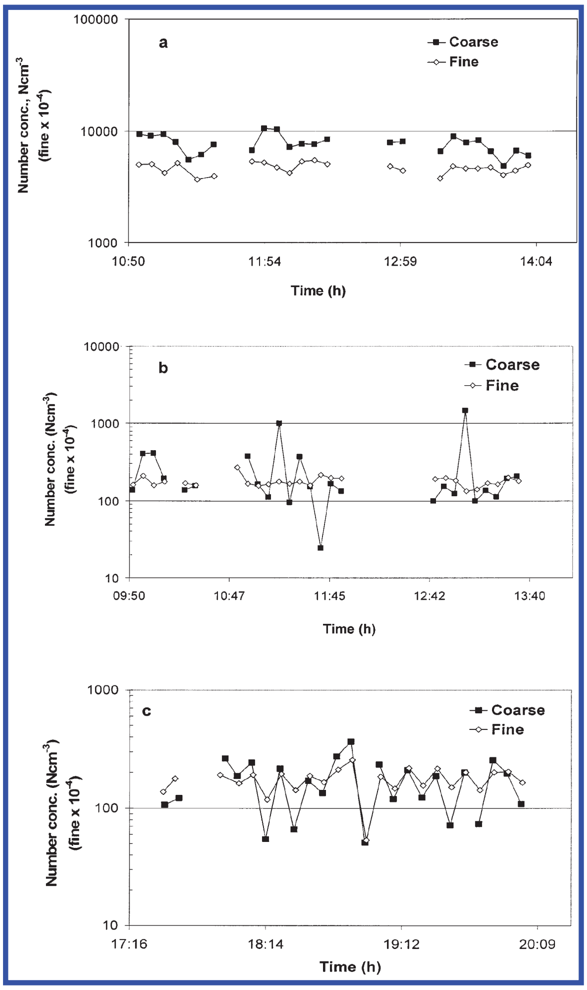

Figure 8. Time variations of fine and coarse particle number concentration during measurements (a) upstream of the ESP, (b) downstream from the ESP, and (c) downstream from the condenser.

particle density of 0.1 g/cm^3 were assumed, a fairly good match between APS and impactor data would be obtained. Possibly the discrepancy between the data is a combination of instrument inaccuracy and a low density.

The Fly Ash Concentration over Time. The fluctuations of the fine and coarse particle number concentrations during the measurements are shown in Figure 8.

In previous investigations, variations of the boiler parameters such as temperature, fuel, and load were vital factors contributing to short time-scale data fluctuation of particle concentration.[14,27] To minimize the influence of such variations, the boiler parameters were kept close to constant during the whole 2 day measurement period.

The fine particle concentration upstream of the ESP was fairly constant (Figure 8a) varying within the range of 3.6 × 10^7 and 5.5 × 10^7 particles/Ncm^3. The coarse particle concentration varied between 3600 and 10700 particles/Ncm^3. There was no obvious covariance between the fine and coarse particle concentrations.

(27) Moisio, M. *Real Time Sizes Distribution Measurement of Combustion Aerosols*, Publication 279; Tamere University of Technology: Finland, 1999; pp 130–140.

Table 3. Mass Ratio of Element to Total Elements (Percent of Listed) in Fly Ash Collected Upstream of and Downstream from the ESP and Downstream from the Flue Gas Condensor[a]

elements (%)	upstream of the ESP		downstream from the ESP		downstream from the flue gas condensor	
	fine mode[b]	coarse mode[c]	fine mode[b]	coarse mode[c]	fine mode[b]	coarse mode[c]
P	0.25	5.1	0.08	4.1	0.11	3.9
S	20.7	12.7	18.2	15.2	17.6	16.8
Cl	12.5	3.7	18.2	6.1	20.0	5.4
K	58.9	27.3	57.2	32.4	56.2	27.8
Ca	2.7	42.8	1.2	33.3	1.1	35.4
Cr	0.71	0.42	0.14	0.07	0.22	0.20
Mn	0.32	3.4	0.25	4.3	0.24	5.2
Fe	0.46	2.7	0.08	1.5	0.12	1.8
Cu	0.05	0.06	0.03	0.05	0.03	0.01
Zn	2.7	1.7	3.7	2.3	3.7	2.9
Cd	0.33	0.29	0.28	0.32	0.31	0.24
Ag	0.36	0.22	0.34	0.26	0.31	0.22
Pb	0.13	0.02	0.17	0.07	0.18	0.07

[a] The measurement of the elemental composition by PIXE. [b] Fine mode: $0.03 < d_{ae} < 1.0$ μm. [c] Coarse mode: $1.0 < d_{ae} < 6.8$ μm.

Downstream of the ESP, the fine particle concentration varied between 1.5×10^6 and 2.5×10^6 particles/Ncm^3. Figure 8a,b illustrates that the relative variation of the fine particle concentrations measured upstream and downstream of the ESP were in the same order. The coarse particle number concentration was less steady than it was upstream of the ESP, varying by a factor of 10 over time. These fluctuations in coarse particle concentration are probably caused by re-entraining of coarse particles, during the rapping process of the collection electrodes. There was no covariance between fine and coarse particle concentration, indicating that there was no substantial re-entraining of fine particles, caused by the electrode rapping.

The APS instrument can operate at close to real time mode, while the scanning SMPS system requires a cycling time, in order of minutes, to scan the size distribution. To get comparable concentration data the sampling time was set to 500 s for both instruments. Hence this time duration might result in a number of rapping cycles in each scan.

Downstream from the condenser, the fine particle concentration, as well as variation, was close to the same as upstream of the condenser, while the coarse particle number concentration was slightly reduced but still fluctuating (Figure 8c). Contrary to data from up- and downstream of the ESP, there is a significant covariance between fine and coarse particle concentrations.

To investigate the separation efficiencies of the ESP and the condenser, it was assumed that the particle concentration and particle size distribution upstream of the ESP were the same during the 2 days of measurement. As shown by Figure 8a–c, there were variations but no clear trends in particle concentrations during the separate measurements. The same is valid also for the particle geometric mean diameter, which varied without exhibiting any trend. These observations confirm the earlier assumption made regarding the constant conditions upstream of the ESP during the whole measurement period.

Compositional Penetration. Particle induced X-ray emission (PIXE) was used to determine the elemental composition ($Z > 12$) of the particle deposits collected on each impactor substrate. To get the elemental composition of the fine and coarse particle size ranges, the amounts from stages 1–7 as well as 8–11 were summed and are given in Table 3. In Figure 9 the main elements in the coarse fractions are represented as bars. Stages 1–7 and 8–11 represent aerodynamic diameters of 0.03–1.0 and 1.0–6.8 μm, respectively. To investigate if there is any change in the elemental composition of particles in any size range at the different measurement locations, the elemental composition is represented as a percentage mass ratio. The percentage mass ratio x_{ij} of an element i, in a specific size fraction j, is given by

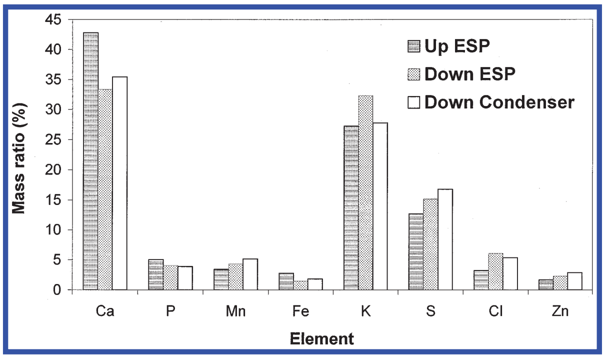

Figure 9. Mass ratio of element to total elements (percent of listed in Table 3) in the coarse fractions.

$$x_{ij} = 100\frac{m_{ij}}{\sum_i m_{ij}}$$

where m_{ij} is the mass of element i, and the denominator represents the mass of all elements listed in Table 3.

The analysis showed that K, S, Cl, and Zn constitute more than 90% of the analyzed elements in the fine mode. These elements might volatilize during combustion, subsequently forming fine particles by nucleation, condensation, and coagulation. In the coarse mode the refractory elements Ca, Fe, and Mn would constitute about 40–50% of the particle mass. These results were found to be the same for all three sampling locations. The elemental composition of particles deposited on each impactor stage is shown in Figure 10, represented as percentage mass ratios. The ratios of K, Cl and Zn, decreased with increasing particle diameter while the Ca and Fe ratios increased with particle diameter.

As indicated in Table 3 and Figures 9 and 10, there are some significant differences in elemental composition and distribution between particles sampled at

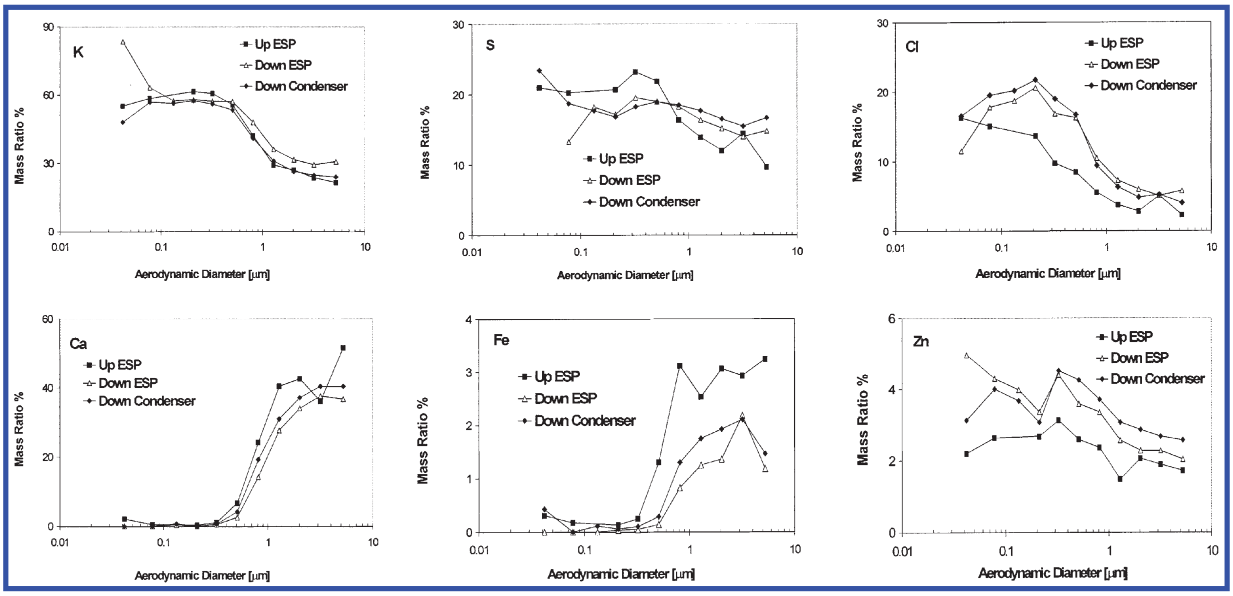

Figure 10. Mass ratio of element to total elements (percent of listed in Table 3) on each impactor substrate.

different locations. In particular this difference is pronounced for the results from upstream and downstream of the ESP.

However the data available is not enough to determine if there is any compositional dependent penetration of particles of a given size. This is partly due to analytical errors, since some of the concentrations are close to the detection limit of PIXE. The comparison might also be distorted by minor changes in fuel composition, which will induce variations in the particle composition. It is also very likely that the coarse particle fraction downstream from the ESP contains particles re-entrained during the rapping of the ESP collection plates. Hence the re-entrained coarse particles are most probably mixed with, or coated by, fine particle material. The results presented in Table 3 and Figure 9 reinforce this assumption. Elements that are more abundant in the fine particle fraction (K, Cl, S, and Zn) are slightly increased in coarse particle fraction downstream of the ESP, while the ratios of Ca and Fe decrease. The change in elemental mass ratios of the coarse fraction is not very large. However the results are consistent for all elements, except for Mn and Cr.

The PIXE data indicate that sulfur was depleted at the two first impactor stages during measurements downstream of the ESP. This observation is inconsistent with previous results where ESP and corona charging was demonstrated to generate gas to particle conversion of sulfur.[8,25] Downstream from the condenser, sulfur is not depleted at the first impactor stage; on the contrary, it seems to be enhanced.

Conclusions

The effects of an electrostatic precipitator and a flue gas condenser on fly ash particle size distribution, particle concentration and particle composition were studied in a 6 MW moving grate boiler fired with moist forest residue. Downstream of the ESP particle number concentration was reduced by 96% both in the fine and coarse particle range. The ESP seemed to have a minimum collection efficiency of about 50% for particles in the 0.3−0.6 μm range. This could be attributed to the actual low collection efficiency for this size range, and possibly also indicating formation of particles in the ESP by agglomeration of smaller particles. There also seemed to be slightly decreased collection efficiency for the largest particles in the coarse mode. The flue gas condenser appeared to have no effect on fine particle number concentration, while coarse particle number concentration was decreased by about 25%. Fine particle concentration was fairly constant over time at all measurement positions. The coarse particle concentration fluctuated more widely, especially downstream from the ESP, where particles re-entraining as a result of ESP rapping influenced the coarse particle concentration. The main elements (Z > 12) in the fine fly ash fraction were K, S, and Cl, whereas the main elements in the coarse fraction were Ca, K, S, and Cl. After passing the ESP the ratio of Ca decreased in the coarse fraction, while the ratios of K, S and Cl increased, indicating transference of fly ash material from the fine to the coarse fraction. There was no significant difference in the elemental composition in any particle size fraction sampled upstream and downstream of the condenser.

Acknowledgment. Financial support from STEM (Swedish National Energy Administration) and TFR (Swedish Research Council for Engineering Sciences) is gratefully acknowledged.

EF020076B