CONDITIONS FOR ELECTROSTATIC PRECIPITATORS AFTER BIOMASS FIRED BOILERS

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ABSTRACT

Efforts are made to increase the use of renewable energy sources to limit the fossil fuel combustion. In 2001 combustible renewable fuels including waste represented slightly more than 10% of the primary fuel supply globally.

Solid biofuels are fired in small units for domestic heating, in grate boilers for district heating and industrial utilisation and in fluidised bed boilers with thermal capacities exceeding 100 MW. Biofuels are also used for co-firing in pulverised coal fired boilers.

There is an increasing concern regarding the particle emissions from biomass combustion. This paper will discuss particle characterisation and particle collection after biomass fired boilers with a thermal capacity exceeding 1 MW. The smallest boilers in this range are often only equipped with a multi-cyclone for collection of the coarse particles in order to meet rather modest particle emission requirements. Larger boilers have more stringent requirements, which need efficient removal also of the fine particles. The electrostatic precipitator (ESP) is the most common choice, due to its robustness and high particle removal efficiency for the complete particle size range.

This paper will deal with properties of particles formed in biomass combustion and the influence on the ESP covering different types of biofuels. Comparisons will also be made with coal combustion.

1. Introduction

In 2001 renewable combustible fuels including waste accounted for more than 10% of the primary energy in the world (1). The contribution is even larger in regions like the Scandinavian countries. In Sweden biofuels including peat accounted for 16% of the energy supplied in 2002 (2). About 50% of the biofuels in Sweden are utilised in the forest industry in combustion of black liqour and wood residues. In ten years biomass combustion for district heating has doubled and represents about one third of the biofuel supply.

Biomass fired boilers with thermal capacities ranging from below 1 up to more than 100 MW are used in the district heating networks. Grate boilers are common in the lower thermal capacity range whereas fluidised bed boilers are more frequent for higher thermal capacities.

In countries like Sweden and Finland biofuels are dominated by wood from conifer trees in different forms, e.g. wood waste from the industry, forest residues or processed biofuels like pellets. Globally biofuels include a wide variety of fuels like agricultural waste, e.g. rice hull, olive and sunflower residues, and other types of wood. Bagasse, a residue from sugar cane, is another frequently fired biomass fuel. Different types of biofuels have very different fuel properties with respect to for example ash content and ash composition (3-4).

There is an increasing need for particle collectors after biomass fired boilers to reduce the particle emissions. The electrostatic precipitator (ESP) is a common choice. Standardised pre-assembled ESP ’s are installed after boilers with a thermal capacity exceeding 1 MW.

Smaller boilers have less stringent the emission limits. Multi-cyclones are then often sufficient to meet the modest particle emission requirements. Multi-cyclones are also often used as pre-collectors upstream ESP's to protect the ESP from glowing particles and fire. The fabric filter (FF) is an alternative if the fire risks have been eliminated.

This paper will focus on the operating conditions for ESP's after biomass fired grate boilers. Some comparisons will be made with the conditions for ESP's after pulverised coal fired boilers (5).

2. Fuel properties

In order to predict the particle properties it is important to understand the particle formation process, which is depending on fuel properties, boiler type and operating conditions.

Generally a combustion aerosol consists of at least two modes. The fine particles dominate the particle number concentration, whereas the coarse fraction usually dominates the particle mass concentration. The fine particle mode is in the submicrometer range usually with mass concentration maximum around 0.1-0.5 μm. The fine mode consists of vaporised material, which condenses as the flue gas temperature decreases. Volatile components are enriched in the fine mode. The coarse mode originates from e.g. minerals included in the fuel.

The fuel and fuel ash compositions are important for the particle formation. In table 1 fuel and fuel ash analyses are compared. Analyses from two Scandinavian wood fuels are compared with South African and Polish coals, which are available on the global market. In addition analyses of rice hull and bagasse from the literature are included (4).

Table 1. Fuel and fuel ash analyses from coal, wood fuels and agricultural waste

Fuel	Biomass Dry wood fuel	Biomass Wood pellets	Rice hulls	Sugar cane bagasse	Coal South Africa	Coal Poland
Proximate analysis (% weight, dry basis)						
Ash	0.31	0.31	20.3	2.4	17.1	14.2
Volatile matter	n.a.	n.a.	63.5	85.6	20.7	n.a.
Fixed carbon	n.a.	n.a.	16.2	12.0	62.2	n.a.
Ultimate analysis (% by weight dry and ash free basis)						
Carbon	51.3	50.7	48.7	49.9	84.8	84.6
Hydrogen	6.4	6.3	6.0	6.0	4.1	5.4
Nitrogen	0.1	0.2	0.7	0.16	2.1	1.5
Oxygen	42.2	42.6	44.5	43.9	8.4	7.5
Sulphur	0.05	0.03	0.06	0.04	0.52	0.87
Ash composition (% by weight)						
P_2O_5	2.0	3.4	0.4	2.7	1.2	0.56
SiO_2	11.4	25.6	91.4	46.6	47.6	47.7
Fe_2O_3	0.8	1.9	0.1	14.1	2.9	7.55
Al_2O_3	2.4	4.4	0.8	17.7	33.2	26.2
TiO_2	0.1	0.3	0.02	2.6	1.7	1.1
CaO	31.6	25.2	3.2	4.5	6.2	3.9
MgO	9.8	5.3	<0.01	3.3	1.3	2.8
SO_3	2.2	2.2	0.7	2.1	4.6	
K_2O	11.1	11.2	3.7	0.2	0.6	2.8
Na_2O	1.1	1.6	0.2	0.8	0.1	1.0

The content of volatile matter is higher for young fuels like biofuels. The volatile material contains except from carbon also oxygen and hydrogen contributing to a higher flue gas moisture content in biomass combustion than for coal.

The Scandinavian wood fuels have low ash contents, < 1 % by weight. Heartwood has a lower ash content than bark, which could have an ash content up to 3-4% by weight (3). Other biofuels like rice hull have a much higher ash content. The ash content in coal varies a lot, but ash contents in the range 10-20% are common on the global market.

In the fuel ash composition the inorganic components are given as their corresponding oxides. Typically wood fuels have high contents of calcium and potassium in the ash. Rice hull and bagasse have high contents of silicon. Coal ash consists to a large extent of components like silicon and aluminium, which are common constituents in minerals.

In the formation of particles from inorganic species it is crucial in which form the inorganic components exist in the fuel. Subsequent leaching of the fuel in water, ammonium acetate and hydrochloric acid is a method to split each inorganic component in four major groups (6). The fraction leached in water is soluble alkali sulphates, carbonates and chlorides. The inorganic material leached in ammonium acetate is mainly organically associated. These two fractions are the most reactive and volatile during the combustion. The material leached in acid is carbonates and the rest remaining minerals. The method has been used both for coals (7) and wood fuels (8). In coal sodium was mainly soluble in water or organically associated whereas potassium was found in minerals like illite. In wood fuels calcium, potassium and magnesium are mainly water-soluble or organically bound. A major difference between the coals and wood is the occurrence of potassium suggesting that potassium in wood is in a volatile form and will be important in the formation of fine particles.

3. Combustion technology

Several techniques are available for solid fuel combustion. The main categories are:

- Pulverised fuel combustion
- Fluidised bed combustion
- Fuel bed (grate combustion)

The combustion technique is chosen based on technical and economical considerations. The grate combustion technique is predominantly used for smaller units, like biomass fired boilers or coal fired boilers for industrial applications. The investment cost is relatively low, but the boiler efficiency is lower than for the other techniques.

The fuel is distributed on the grate with e.g. a spreading device or a screw conveyer. As the fuel is moving on the grate it will go through drying, volatilisation and char combustion. The primary air is distributed through the fuel bed. Secondary air is introduced after the grate in order to achieve complete combustion. The excess air has to be higher than in pulverised fuel combustion to get acceptable combustion conditions.

Volatile inorganic components vaporise at the combustion temperature and leave the combustion zone as gases and condense as the flue gas temperature decreases. Coarse material consisting of unburned fuel particles and ash particles will follow the flue gas at high primary airflow or not evenly distributed primary air. These particles will be treated together with the condensed material in the flue gas cleaning system.

Fluidised bed combustion is used for larger biomass or coal fired boilers. Often this combustion technique is used for fuel mixtures of for example coal, biomass and different types of waste products. In fluidised bed combustion (FBC) air is passing through a bed of solid particles. As the airflow increases the bed will behave like a fluid. In circulating fluidised bed combustion the solid material is filling the whole combustion chamber and material leaving the combustion chamber is continuously re-circulated to keep the content of solid material constant. The bed material is a mixture of inert material (sand) and fuel. Limestone or dolomite is used as bed material for sulphur removal, if the fuel has a high sulphur content. The combustion temperature is considerably lower for FBC boilers than for PC boilers, which suppress the volatilisation of inorganic components and the formation of thermal NO_x. Non combusted coarse particles are separated in the boiler cyclone and returned to the combustion chamber. Particles that are too fine to be separated in the boiler cyclone will be treated in the flue gas cleaning system.

The pulverised fuel combustion technique is preferably used for large units, since the technique is associated high investment costs for boiler and fuel preparation. The fuel is ground in mills and the pulverised fuel is then supplied with the primary air to the burners. The combustion takes place at relatively low excess air level. The boiler efficiency is usually high. Most of the inorganic material in the fuel (ash) and products from incomplete combustion will be carried with the flue gas to the flue gas cleaning system. Presently biomass fuels are to an increasing extent co-combusted with coal in pulverised coal fired boilers (9).

4. Particle characterisation after wood fired grate boilers

Characterisation of particles formed in wood fired grate boilers has been made in detail. The focus has been on boilers with a thermal capacity in the range of 1-10 MW. The flue gas cleaning system consisted of either multi-cyclone only or multi-cyclone with ESP installed downstream. A flue gas condenser was in some cases installed after the ESP to further increase the thermal output of the boilers. Forest residues with rather high moisture content, waste products from the wood industry and processed fuels like pellets were fired in the different units.

4.1. Particle sampling system and instrumentation

Simultaneous measurements with several particle characterisation instruments were made. The particle sampling system is shown in figure 1.

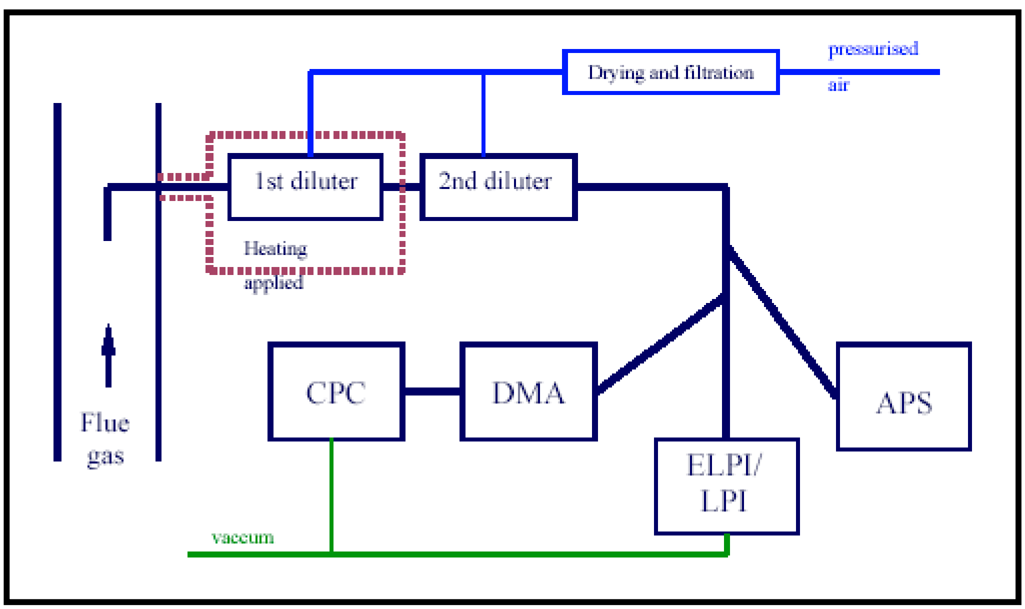

Figure 1. Particle sampling system

Flue gas was extracted from the duct in a nozzle selected to get isokinetic sampling. The flue gas was then diluted and cooled with dry and clean pressurised air. The particle number size distribution was determined with differential mobility analyser/condensation particle counter (DMA/CPC) and aerosol particle sizer (APS) for the submicrometer fraction and coarse fraction respectively.

The particle mass size distribution was measured with a low-pressure impactor (LPI). The LPI is a cascade impactor with 13 separate stages for particles with an aerodynamic diameter in the range from 0.030 μm to 10.33 μm. The time resolution is in the order of one hour with this set-up. The chemical composition of collected particles was analysed for the different stages using particle induced X-ray emission (PIXE).

The electrical low-pressure impactor (ELPI) was used to get the particle number size distribution with a very high time resolution (~5 s). At the ELPI inlet all particles are charged. The particles are then separated based on their aerodynamic diameter as in an ordinary LPI. The current from each stage is then measured and converted to a particle size distribution.

There are significant particle losses in the sampling nozzle and diluter systems. Corrections for losses have been made for particles < 5 μm based on penetration curves for the sampling system made in the laboratory. Reliable measurements of larger particles cannot be made with this set-up. The total particle mass concentration was measured with thimbles in the duct as a complement.

4.2. Particle mass concentration and particle mass size distribution

The total particle mass concentration after the boiler varies a lot. The design inlet particle concentration to the particle collection system is often in the range 3-5 g/Nm^3 (dry gas, 13% CO_2). The actual concentration is often significantly lower. As an example the particle concentration upstream the multi-cyclone after a grate boiler firing forest residues was only 0.35 g/Nm^3 (dry gas, 13% CO_2).

Studies show that there is a significant influence of operating conditions on the total particle mass concentration also after the multi-cyclone (10). A boiler load increase from low load to medium load in a boiler firing dry wood residues increased the total particle mass concentrations after the multi-cyclone from about 50 to 100 mg/Nm^3 (dry gas, 13% CO_2). Forest residues have considerably higher ash content than the dry wood fuel. The total particle mass concentrations after two different boilers firing forest residues were 150-175 mg/Nm^3 (dry gas, 13% CO_2) at medium to high boiler load.

The particle mass size distribution is important for the ESP efficiency. LPI measurements were made after the boiler firing dry wood fuel at three different boiler loads. The results are shown in figure 2.

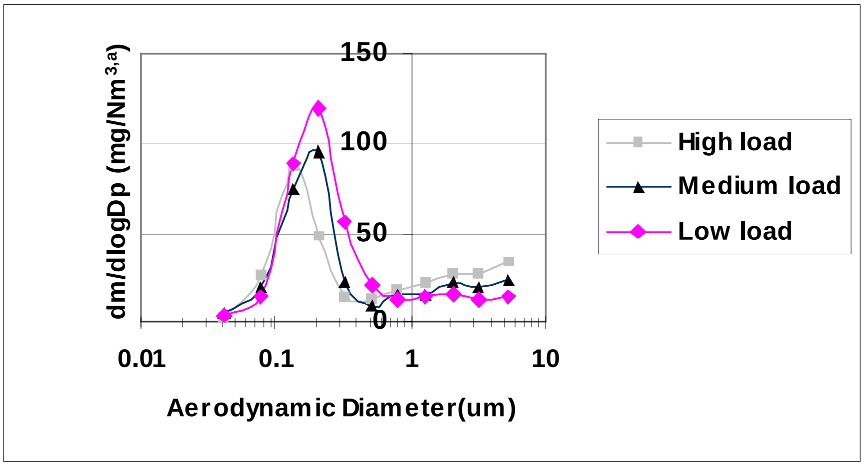

Figure 2. Particle mass size distributions after the boiler firing dry wood waste as measured downstream the multi-cyclone

There are only minor differences in the size distributions. The mass concentration in the fine particle mode (<0.8 µm) was 45-65 mg/Nm^3 (dry gas, 13% CO_2). The differences in total particle mass concentration are explained by an increasing fraction of coarser particles at higher loads.

A total particle mass concentration around 150 mg/Nm^3 (dry gas, 13% CO_2) is too high to comply with the emission standards in many installations. Recently plants have installed ESP's downstream the multi-cyclones to further reduce the particle emissions.

The particle mass concentrations after single field ESP's installed downstream the multi-cyclones after grate boilers firing forest residues have been investigated. After one boiler the ESP reduced the total particle mass concentration from around 175 mg/Nm^3 (dry gas, 13% CO_2) to below 5 mg/Nm^3 (dry gas, 13% CO_2). In another case LPI measurements showed a reduction from 135 to 16 mg/Nm^3 (dry gas, 13% CO_2), i.e. 88% removal efficiency. The particle removal efficiency for particles in the fine mode was 83%, i.e. slightly lower than average (11). The particle mass concentration in the fine mode was reduced from 76 to 13 mg/Nm^3 (dry gas, 13% CO_2). The particle mass size distributions upstream and downstream the ESP is shown in figure 3.

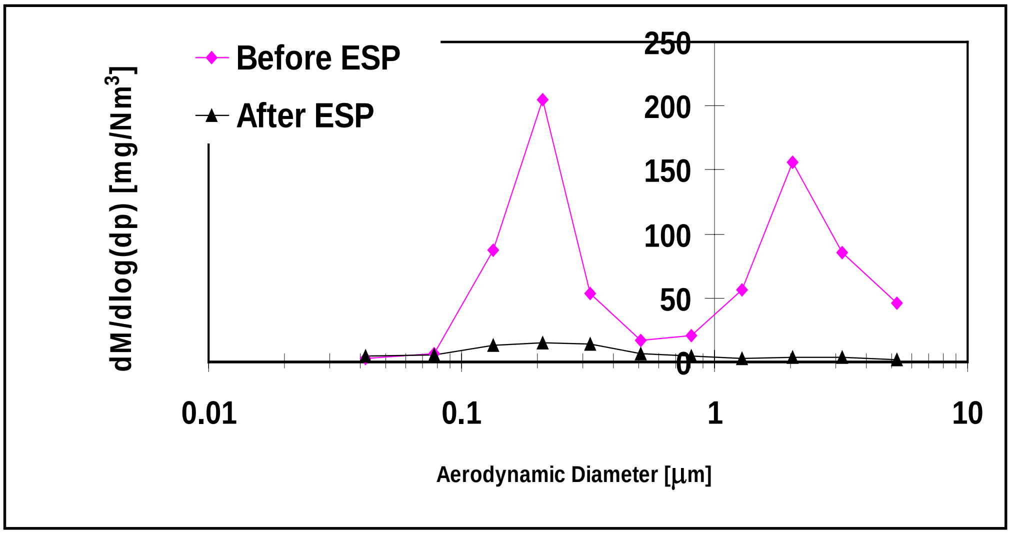

Figure 3. Particle mass size distributions upstream and downstream the ESP after a grate boiler operating on forest residues

In general the measured particle emissions after ESP's installed after biomass fired grate boilers are well below the guaranteed emissions both as a result of deviations from design data, i.e. lower flue gas flow and lower inlet dust concentration and a better performance than expected. Figure 4 shows measured emissions from a large number of ESP installations after wood fired grate boilers as a function of relative SCA (specific collecting area). The measured emissions show, that low particle emissions < 10 mg/Nm^3, frequently are achieved.

The particle mass size distribution was measured after a fluidised bed boiler operating on wood/peat and on a mixture of wood/peat and waste fuel with a high ash and chlorine contents (12). The particle mass concentration in the fine particle mode increased from average 30 mg/Nm^3 to 73 mg/Nm^3 when changing to the fuel mixture with waste.

The particle mass concentration after a pulverised coal fired boilers is typically 10-20 g/Nm^3 for coals available on the global market. Typically only 1% of the inorganic material in a high-rank coal vaporises during the combustion and is found in the submicrometer fraction (13). The mass concentrations in the fine submicrometer particle mode are similar for pulverised coal fired boilers and wood fired grate boilers.

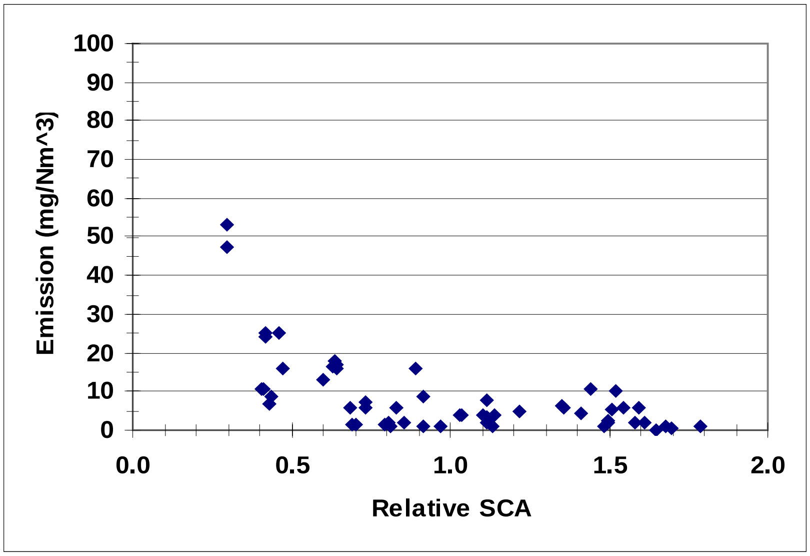

Figure 4. Measured emissions after wood fired grate boilers as a function of relative SCA

4.2. Particle number concentration and particle number size distribution

The particle number concentration is dominated by the fine particles. The total particle number concentration is similar for pulverised coal fired boilers and biomass fired grate boilers. The total particle number concentration measured with DMA was in the ranged from $1.6 \cdot 10^7$ to $3.4 \cdot 10^7$ particles/ cm^3 upstream the ESP in the range 0.02-0.54 μm after pulverised coal fired boilers firing Colombian and South African coals (14).

After biomass fired grate boilers the number concentration in the mode < 0.3 μm was in the range from $2 \cdot 10^7$ to $9 \cdot 10^7$ particles/ cm^3 (dry gas, 13% CO_2). The particle number size distributions were measured downstream the multi-cyclone after the grate boiler fired with dry wood with ELPI at three different loads. The results are shown in figure 5.

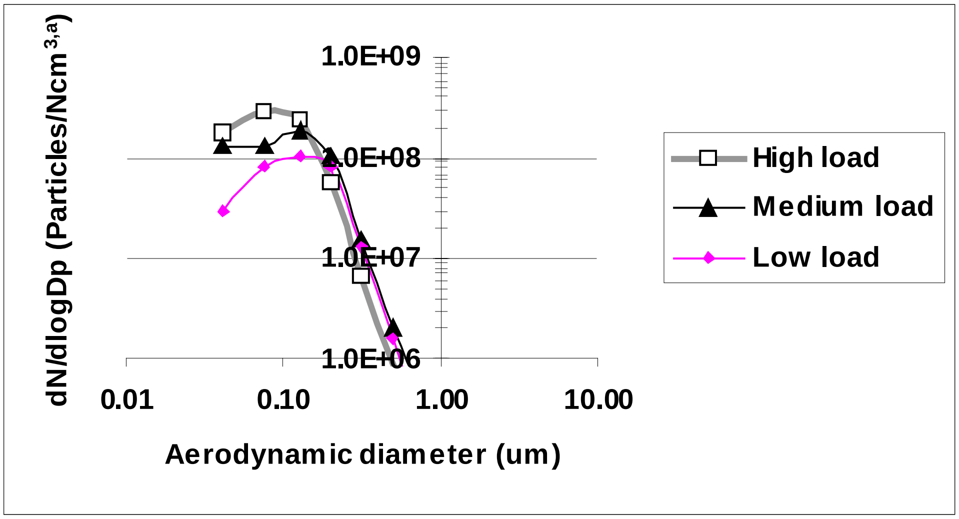

Figure 5. Particle number size distribution downstream a multi-cyclone after a boiler firing dry wood

Decreasing boiler load showed a small shift towards lower particle number concentration and slightly larger particles.

4.3. Chemical composition of particles

It is of interest to understand the chemical composition of particles in different size ranges. Table 2 shows a comparison of the chemical composition of particles in the fine and coarse mode respectively. The analyses are from a grate boiler fired with dry wood and a pulverised coal fired boiler firing Polish coal.

Table 2. Chemical composition of particles in the fine and coarse mode respectively.

Boiler	Pulverised coal		Grate boiler	
Fuel	Polish coal		Dry wood fuel	
Reference	Ref.15			
Test location	After ESP		After multi-cyclone	
Method	GFAAS/PIXE		PIXE	
Total conc. (mg/Nm^3)	24.3		67	
	Fine mode Dstokes <0.2 μm	Coarse mode	Fine mode	Coarse mode (< 5 μm)
Total (mg/Nm^3)	1.5 (6%)	22.8 (94%)	36 (54%)	31 (46%)
Mass fraction analysed (%)	38	27	33	23
Na	1.3	2.2	n.a.	n.a
Mg	3.0	6.7	n.a.	n.a.
Al	7.7	22.7	1.7	3.5
Si	17.1	29.7	3.9	6.9
S	26.9	0.7	13.3	3.5
Cl	n.a.	n.a.	3.5	4.4
K	2.1	3.7	59.4	19.0
Ca	31.0	13.7	10.9	51.9
Ti	1.1	2.2	< 0.0	0.3
Fe	7.7	16.8	0.3	0.7
P	n.a.	n.a.	1.1	1.1

The biomass fired grate boiler gives a fine mode of potassium salts like sulphates and chlorides. Potassium has not the same volatile form in the coal. The fine particle fraction for the Polish coal seems to be calcium sulphate.

4.4. Particles from incomplete combustion

Except from ash originating from inorganic material in fuel the fly-ash also contains material formed due to incomplete combustion. The content of incompletely combusted material is determined by analysing the loss of ignition (LOI). LOI for fly-ashes from wood fired boilers is measured at a relatively low temperature, 550 °C, in order to avoid losses of volatile inorganic components. The loss of ignition for fly-ashes from coal fired boilers is measured at two temperatures, 640 and 840 °C respectively.

The LOI can be high for wood fired grate boilers. For one boiler LOI in the collected ash increased from 28% at low boiler load to 72% at high boiler load. This is a result of increasing entrainment of material from the fuel bed.

Multi-cyclones are often used to protect the ESP from coarse glowing fuel particles. LOI was measured for dust collected in the multi-cyclone and in the ESP separately. In this case LOI was 26% for the multi-cyclone ash and only 3% for the ESP ash.

LOI in ash after a coal fired pulverised boiler is typically 2-3%.

The content of unburned material is an important parameter for the ESP operation not only as potential fire risk. The unburned material has a low resistivity and can contribute to reduce the dust cake resistivity. Also large hollow particles with a low resistivity can easily get re-entrained in the flue gas. It is therefore important to keep the flue gas velocity in the ESP low under such conditions.

4.5. Electrical properties

The electrical properties of the dust are important for the ESP performance. High resistivity causes back-corona conditions, which result in decreased ESP particle removal efficiency. The resistivity of dust collected in the ESP was analysed in an atmosphere of air with the same moisture content as in the actual flue gas. Figure 6 shows measured resistivity for fly-ash collected in the last fifth ESP field after a pulverised coal fired boiler firing South African coal and fly-ash collected in a single field ESP installed downstream a multi-cyclon after a biomass fired grate boiler.

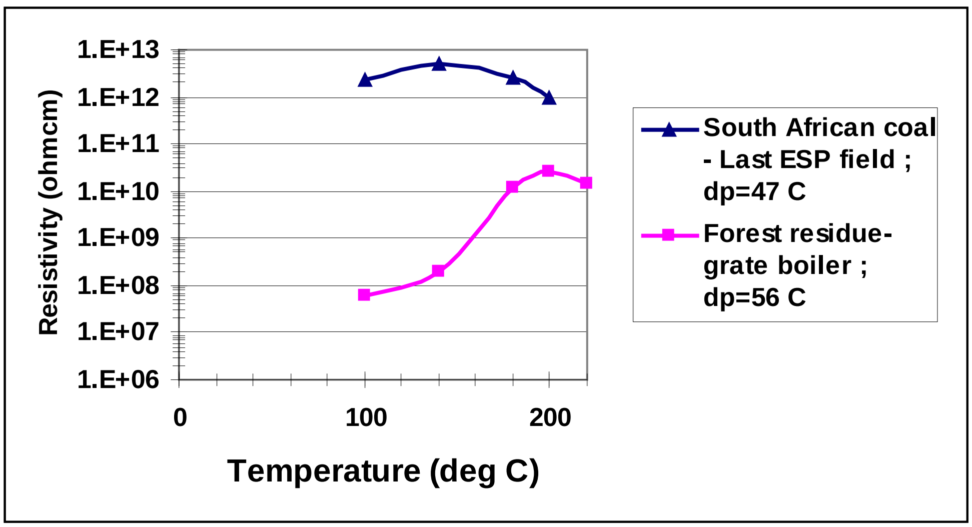

Figure 6. Resistivity of fly-ash collected in the last ESP field after a boiler firing South African coal and in a single field ESP after a grate boiler firing forest residues

The resistivity for the fly-ash from pulverised coal combustion is several orders of magnitude higher than for the fly-ash from forest residue combustion. There is certainly a large variation between different coal fly-ashes, but generally it is higher than for ash from wood combustion. An exception is wood with a high salt content generating ash with a high chloride content (16).

The lower resistivity is a result of higher moisture content in the flue gas, the fly-ash composition and a high content of particles from incomplete combustion.

5. Conclusions

Biomass combustion is increasingly used to utilise renewable energy sources. Biomass fuels are predominantly fired in relatively small units, where grate boilers often are the most economical selection. Recently mechanical collectors like multi-cyclones are replaced or complemented by ESP's to further reduce the total particle mass concentration and to reduce the emission of fine particles.

The total particle mass concentration upstream the flue gas system varies strongly with operating conditions like boiler load. The total particle mass concentrations after multi-cyclones varied from 50 to 175 mg/Nm^3 (dry gas, 13% CO_2) after wood fired grate boilers depending on boiler load and fuel. The mass concentration in the fine submicrometer mode is in the range 45-75 mg/Nm^3 (dry gas, 13% CO_2), which is comparable with pulverised coal combustion. ESP's in most cases achieve low particle emissions, < 10 mg/Nm^3, due to efficient removal of particles in the complete particle size range.

The wood ash composition shows high concentrations of potassium and calcium. The potassium is available in a reactive and volatile form. The fine particle mode shows therefore an enrichment of potassium salts like sulphates and chlorides.

The resistivity is in general low for wood fly-ashes compared to coal fly-ashes. The ESP operation will normally not be affected of back-corona caused by high resistivity.

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