Charging- and removal efficiency of an ESP in a 250 kW biomass boiler

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1 Abstract

The combustion of biomass creates ultra fine particulate matter which is not precipitated by traditional multi cyclone technique, usually adopted on small scale plants. In Sweden the number of small bio fuelled plants is increasing and there is a need for cost effective means to precipitate the ultra fine particles formed. One such technique may be electrostatic precipitation, but the economy of scale is a constraining factor for systems commercially available today. This paper describes field tests of a low cost electrostatic precipitator, ESP, including not only investigation of collection efficiency, but also measurement of charging effectiveness. The aim of the tests was to determine the potential for the low cost ESP design to form part of an electrostatic precipitation system for use on bio fuelled plants in the megawatt scale. The charges acquired by the particles have been measured using a low pressure cascade impactor, ELPI. Measurements of charges were carried out on particles escaping from the ESP. The results of the measurements of particle charges indicates that the method may correctly reflect the mean charge levels of particles of the different sizes usually found within the fine particle mode of flue gases from biomass combustion.

2 Introduction

The effect on health from long term exposure to fine and ultra fine particulate matter, PM, especially in combination with pre-existing cardiopulmonary diseases, has led the WHO to issue guidelines, and also led to EC directives on limits of yearly as well as daily average exposure limit [1]. The origin of particulate matter may be both natural and anthropogenic, with health effects varying with the particle's size, chemical composition and morphology. Coarse particles are in general not respirable, but are instead caught by the human respiratory system protection mechanisms and subsequently disposed of. Small particles, on the other hand, may pass through the respiratory system and deposit in the alveolar region in the human lung. Even though there is no distinctive limit between respirable and nonrespirable particles, the sizes below 10 µm (PM_{10}) has been accepted as a range for monitoring and regulatory purposes by most regulatory agencies so far, but also the range below 2.5 µm ($PM_{2.5}$) is referred to by e.g. World Health Organization, WHO [2].

2.1 Increased demand for small ESPs adopted for biomass

The more stringent requirements as set forth by different regulatory bodies are resulting in enhanced requirements on appliances emitting particulate matter to the ambient air [3].

Combustion of biomass creates submicron particles and the use of biomass in relatively small plants, below 10 MW thermal power, is increasing in Sweden. The economy of scale prevents the use of ESPs for removal of these particles [4]. Since there are few other alternatives for removal of submicron particles, such as bag filters [5], there is a current need for adopting the ESP technology to make it feasible also for plants below some 10 MW thermal power.

2.2 Particles from biomass combustion

During combustion of any liquid or solid fuel, particles will form from the ash contained in the fuel. The fraction of ash varies between different fuels. This is true also for biofuels where the ash content varies from a fraction of a percent to more than 10 percent by weight in the dry substance. Some of the ash may be deposited in the furnace or convection part of the combustion appliance, whilst some ash will be carried as cinder with the flue gas.

The particulate matter in the flue gas from biofuel combustion has basically two different origins, usually forming a bimodal particle distribution. The coarse mode is formed directly from debris of ash present in the fuel, whilst the fine mode is formed as a secondary aerosol, where volatile ash components are evaporated in the furnace are subsequently nucleated and condensed, due to the successively decreasing temperature and changes of the chemistry of the flue gas atmosphere.

Fixed bed combustion of solid biofuels, e.g. woody biomass, gives rise to particulate matter in the flue gas with a distribution of mass for which the fine mode is dominating, leaving only a small fraction of mass in the coarse mode.

For plant sizes now under consideration, below 10 MW, fired with woody biomass, the grate firing technique is usually applied. Even though a grate furnace may well, at high loads, release a large number of coarse particles to the gas, thus increasing the fraction of mass in the coarse mode, the particle mass in the fine mode will still remain dominant for the typical plant, which is normally provided with a multi cyclone.

An ESP designed for domestic boilers and stoves has been tested in a 250 kW boiler, where not only removal efficiency, but also particle charges have been studied.

3 Experiments performed

A newly erected plant comprising of a 250 kW boiler, automatically fired with wood chips and producing hot water for heating purposes, was equipped with dual ESPs in series. The ESPs were of a small size and inexpensive. Both collection efficiency and particle charging was studied. The aim of the experiments was to investigate the potential of the design for use as part of a precipitation system for plants in the MW scale. Such intended larger systems are likely to include additional secondary particle traps or collection fields relying on low or no external electrical feed.

3.1 Plant

The hot water boiler (Arimax Bio 250, Ariterm OY, Saarijärvi, Finland) has an internal furnace provided with a stepped grate with longitudinal fire bars of which every second row is movable in longitudinal direction. The intended fuel is pellets or wood chips with a maximum moist content of 40 % by weight on fuel basis. The fuel is fed into the boiler intermittently by means of a feeding screw.

The boiler flue gas is passed through a common multi cyclone dust collector, before entering the flue gas ducting.

The boiler control is governing fuel feed, grate movement, three air supply fans and one flue gas fan, all on a continuous basis and proportional to the prevailing heat demand.

3.2 Plant modifications

The flue gas ducting was provided with two units in series of the ESP intended for testing, together with a bypass line and dampers in order to control the flow through the ESPs, thus simulating also parallel installations.

In order to govern the boiler load, a cooler was installed. The furnace was slightly modified internally in order to maintain an effective combustion when using high moist (50-55%) fuel. These measures resulted in a stable flue gas, representative for a well maintained grate boiler fuelled with woody biomass.

3.3 Tested Equipment

The tested ESP (KW-Zumikron T 150, Kuzner + Weber Gmbh, Maisach, Germany) is of an inexpensive design. The ESP is intended for biomass fuelled plants having a maximum thermal power of 40 kW. The geometry is of wire in tube type, and based on previous work on a small scale ESP carried out by Schmatloch and Rauch [6]. It consists of a metallic pipe, similar to a standard stainless steel flue gas pipe with an angular branch. Through the angular branch a high voltage connection is protruding into the pipe and carries the discharge electrode. The discharge electrode is of 0.1 millimetre diameter and made from tungsten. The particles are collected on the inside wall of the pipe. No device for cleaning the collection surfaces is provided. The principle arrangement is shown on Fig. 3-1.

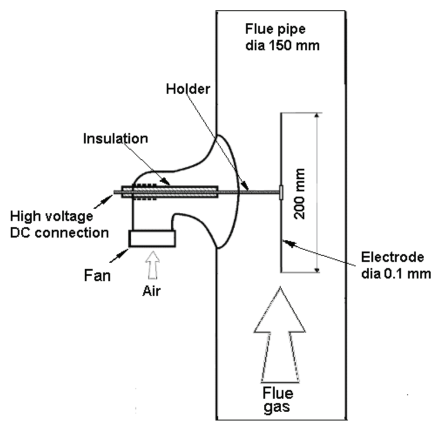

Fig. 3-1: The inexpensive ESP tested for its potential to form part of a precipitator system intended for MW scale biomass plants

3.4 Sampling and measuring

The sampling of flue gas for particle measurements was made using a probe with dimensions and sample flow resulting in near isochinetic conditions. The point of sampling was located at a distance of about five diameters away from the ESPs and downstream a bend of the duct which effectively screened the sampling probe from any electric field.

To measure particle concentration the following two instruments were connected to the sampling line in parallel: Scanning Mobility Particle Seizer (SMPS 3080, DMA 3081 and CPC 3010, TSI Inc, Minnesota U.S.A), Aerodynamic Particle Seizer (APS 3321, TSI Inc, Minnesota U.S.A)

To measure the charge of particles, and in some instances also to measure particle concentration, an electric low pressure cascade impactor was used (ELPI, Dekati Ltd, Tampere, Finland).

The measuring range, with respect of particle concentrations, for the above instruments are well below the particle concentrations usually encountered in flue gases. Therefore, the sample was diluted with air. The air for dilution was dried and filtered through micro pore filters to provide an air of a suitable quality. The dilution was made in two stages, with the first stage provided with heating of the air flow to avoid condensing of water vapour. The dilution ratio is governed by the ratio of dilution and excess flows respectively, which are all controlled.

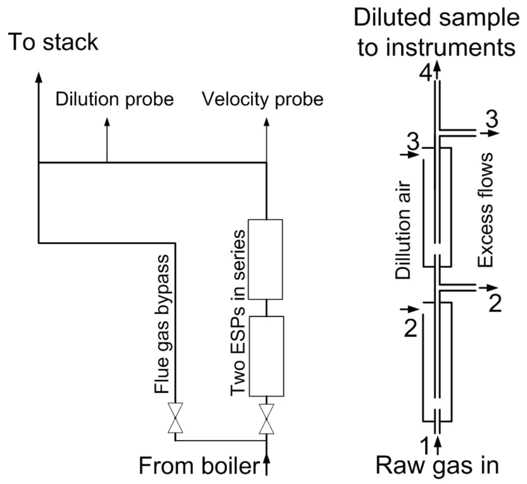

Fig. 3-2: To the left is shown the position of the two tested ESPs in the modified flue gas lines, together with the sampling points. To the right is shown the principle arrangement of the dilution probe.

3.5 Measuring of particle charges

The ELPI instrument contains a sensitive electric measuring system which is designed for quantitative analysis of particle concentrations at a high time resolution. The principle of the instruments is a low pressure cascade impactor, where each impactor stage is electrically insulated from the neighbouring stages. Before the impactor inlet a corona charger is used to charge the particles. At the time the particles are collected on the impaction plate in an impactor stage, the particle charge is delivered to that plate and registered as a small current by an electrometer specifically designated to measure the electric current from the same impactor stage. The instrument is provided with 12 measuring channels working in parallel and calculates particle concentrations for each stage, based on a constant sample flow through the impactor [7]. The instrument is schematically shown on Fig. 3-3.

For measuring of particle charges, the instrument has been used with the corona particle charger switched off. The particles are collected in the different impactor stages and any charges born by a particle will be discharged to the collector plate and registered by the instrument through the corresponding electrometer current.

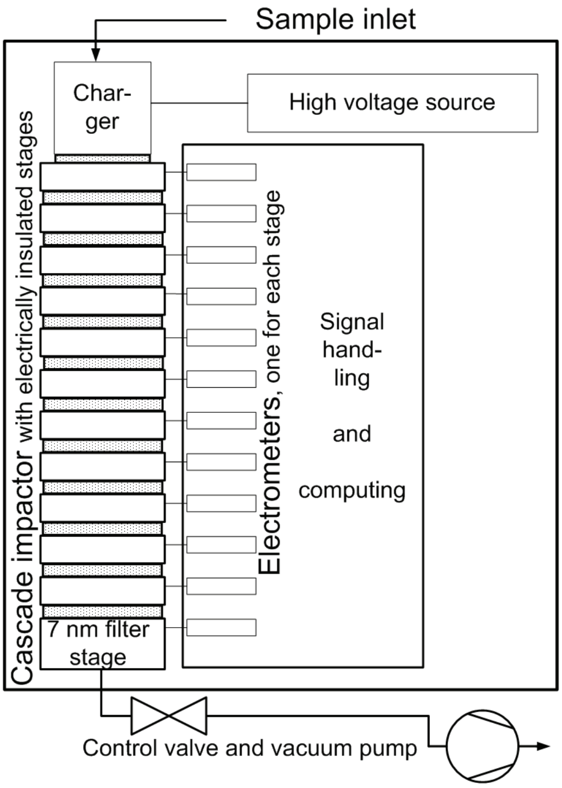

Fig. 3-3: Principle of the Electric Low Pressure Impactor, ELPI

The mean number of elementary charges carried by particles within a size range, i.e. in an impactor stage, has been calculated using the following relationship:

$$n_e = \frac{I}{QC_n e} \qquad (1)$$

Where, for an impactor stage

n_e is the mean number of charges per particle

I is the current

Q is the volumetric flow through the impactor

C_n is the number concentration of particles

e is the elementary charge (6.02x10^{-19} C)

4 Results and discussion

Particle concentrations were measured downstream the ESPs and, when provided, downstream the added particle trap. Measurements were made with voltage feed switched on and switched off, from which results the different collection efficiencies were calculated. Similarly, the charge of the particles escaping the precipitation system was recorded , using the electric low pressure impactor with its corona charger switched off.

4.1 Collection efficiencies

Collection efficiency characterizes the ability of a filter to precipitate particles and is commonly used to describe the effectiveness of a filter. It may be expressed as [8]:

$$\eta_E = \frac{C_{in} - C_{out}}{C_{in}} \qquad (2)$$

Where

η_E is the collection efficiency of the filter

C_{in} is the particle concentration at the filter inlet

C_{out} is the particle concentration at the filter outlet

As may be seen from Fig. 3-2 all the aerosol samples were drawn from one common point downstream the ESPs. The filter inlet particle concentration has been taken as the concentration obtained with both the ESPs switched off, considering the minor losses occurring in the flue gas duct being negligible.

Several filters in series, working independently from each other, will have an overall efficiency described by the relationship [8]:

$$\eta_{Eres} = 1 - (1-\eta_1)(1-\eta_2)...(1-\eta_n) \qquad (3)$$

Where

η_{Eres} is the resulting collection efficiency

η_1, η_2 and η_n are the respective collection efficiencies for the individual filters

For all of the following results, the different collection efficiencies are given separately within the different particle size ranges, thus reflecting the size dependence for the collection efficiency.

On Fig. 4-1 the size dependent collection efficiency is shown from a test of two filters in series at a gas velocity well above the design value. The collection efficiency is varying over the size range. When considering a mean collection efficiency over the size range, it will be necessary to take the various particle concentrations throughout the size range into account. Consequently, the range corresponding to higher concentrations will dominate the mean collection efficiency. The figure shows a collection efficiency between 0.3 and 0.4 in the 40 to 120 nm range for a single filter, and between 0.55 and 0.65 for dual filters in the same size range. The improvement related to the second filter is in line with the calculated value for a second independent filter added to the single one. The result indicates that the filters are working independently and do not influence each other.

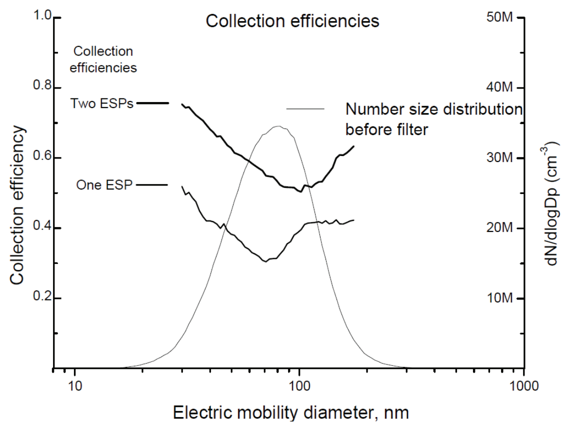

Fig. 4-1: Collection efficiencies based on SMPS data for one ESP respectively two ESPs in series at a gas velocity of 2 m/s through the ESPs

A particle trap consisting of loosely packed steel wool for a duct length of one diameter was added downstream the ESPs. Such a particle trap will, in addition to impaction, rely also on the space charge for precipitation, if the particles leaving the ESPs are electrically charged.

As can be seen from Fig. 4-2, the particle trap, added after the two ESPs, gives an improvement of the total collection efficiency which is of the same magnitude as expected if a third ESP would have been added after the two ESPs.

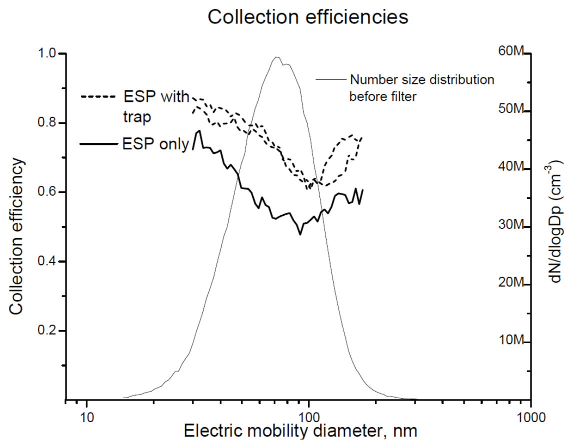

Fig. 4-2: Collection efficiencies based on SMPS data for two ESPs in series with and without the additional particle trap at a gas velocity of 2 m/s through the ESPs

The collection efficiency for two ESPs in series with the particle trap added has been measured also using the ELPI. The results are shown on Fig. 4-3. The resulting collection efficiencies in the particle size range between 40 and 120 nm is between 0.80 and 0.65 for both SMPS and ELPI measurements. When comparing Fig. 4-2 and Fig. 4-3 it should be noted that the particle size distribution is for SMPS measurements based on number, whilst for the ELPI measurements the size distribution is based on mass.

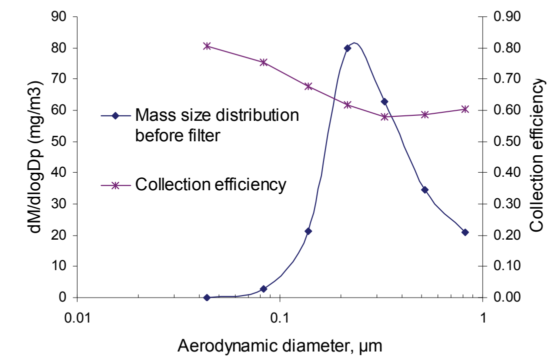

Fig. 4-3: Collection efficiency based on ELPI data for two ESPs in series together with the additional particle trap

4.2 Charges carried on penetrating particles

One aim of testing the small scale ESP was to investigate its potential for use in a larger system. From this point of view the ability of charging particles was tested. On Fig. 4-4 is shown the mean number of elementary charges per particle escaping the ESP as a function of particle size.

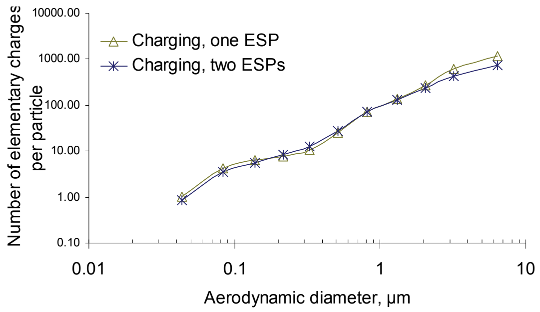

Fig. 4-4: Normalized charge of particles penetrating one and two ESPs respectively

The results show, as expected, that the tested ESP under the high flow rates from the 250 kW boiler gives moderate collection efficiencies. The particle charging process is known to be comparably fast, resulting in charging also of particles which are escaping from the ESP, due to a too short residence time caused by the high gas flow. Such charged particles may well be collected in secondary equipment, with no or comparably low voltage supply, forming a cost efficient ESP system for small bio fuelled plants.

It may be noted from the results presented, that there is no difference in the mean number of charges carried by particles penetrating the system when one respectively two ESPs are activated. This finding indicates that already one ESP causes the particles to be charged up to some limit. The number of charges received by a particle is limited by a saturated state or, below this saturation limit, of the combined action of ion concentration, field strength and time. The number of elementary charges acquired by a spherical, solid particle during a time t in an electric field E with a ion number concentration N_i may, with diffusion charging neglected, be expressed as [8]:

$$n(t) = (\frac{3\varepsilon}{\varepsilon+2})(\frac{Ed_p^2}{4K_E e})(\frac{\pi K_E e Z_i N_i t}{1+\pi K_E e Z_i N_i t}) \quad (4)$$

where

ε is the dielectric constant

K_E is a constant of proportionality

for SI units $K_E = 9 \cdot 10^9$ Nm^2/C^2

d_p is the particle diameter

Z_i is the mobility of the ions

The approximate number of elementary charges acquired by a spherical, solid particle during a time t in a ion number concentration N_i may, with field charging neglected, be expressed as [8]:

$$n(t) = \frac{d_p kT}{2K_E e^2} \ln[1 + \frac{\pi K_E d_p \bar{c}_i e^2 N_i t}{2kT}] \quad (5)$$

where

k is Boltzmann's constant

T is absolute temperature

$\bar{c}_i$ is the mean thermal speed of the ions

The above expressions give clear limits for particle charges, depending on the values of the constituting parameters. The test results clearly reflect, with respect to particle charges on penetrating particles, a limit which is not influenced by the activation of a second ESP.

5 Conclusions

The collection efficiencies at flow rates higher than design values are, as expected, moderate. It could well be expected that two ESPs in series would influence each other, since the second ESP is receiving already charged particles escaping from the first ESP. Such already charged particles will pass the full length of the field in the second ESP and thus having a high probability of being collected. The test result does not support this assumption.

If particles escaping the ESP are carrying charges, a space charge is created. Such a space charge will, if it is strong enough, support particle collection in an additional stage, also if no electrostatic field is obtained from an external voltage feed. Test results, using a particle trap without any external voltage field and placed after two ESPs in series, indicates a collection efficiency of similar magnitude as one ESP. This finding supports the assumption that a space charge, strong enough to support the particle collection, is created after the two ESPs.

There are, for field charging as well as for diffusion charging, limitations for the number of charges a particle of a certain size may acquire during certain conditions. The test result clearly shows a limited charge of particles, which is not influenced by the addition of a second ESP. This finding indicates that the method correctly reflects the charging limit of the particles penetrating the ESPs.

6 Literature

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