A Novel Method for Particle Sampling and Size-Classified Electrical Charge Measurement at Power Plant Environment

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Abstract: In this work we have combined the Electrical Low Pressure Impactor ELPI (Dekati Ltd., Finland) with an FPS-4000, Fine Particle Sampler also made by Dekati Ltd. to measure combustion aerosol particle concentration, size distribution and size-classified electrical charge in power plant environment.

We show how the FPS is used to take the sample from power plant stack before and after the ESP, we show how the sample is diluted, conditioned and temperature decreased in a controlled way and how the ELPI is then used to determine the particle size distribution, concentration and charge levels in different size classes. We discuss about the effects of sampling and dilution for the particle charge levels and losses.

We present the construction and operation principle of each part of the system and how different parts are calibrated for accuracy and for particle losses. We show how the system has been applied for demanding power plant environment and finally present measurement results from pulverized coal power plant showing ELPI measurement results compared to gravimetric impactor measurement showing good agreement between different methods.

Keywords: ELPI, dilution, sampling, FPS, charge measurement

1 INTRODUCTION

Electrical Low Pressure Impactor ELPI (Dekati Ltd., Tampere, Finland) has long been used for aerosol particle size distribution, concentration and size-classified particle charge distribution measurements in power plant environment as well as in other industrial applications[1,2].

In typical combustion aerosol measurements a measuring device is just one part of the whole system but not all; sampling system can affect the results a lot. When measuring hot flue gases sample temperature, humidity and concentration must be decreased in a controlled way and this plays significant role in aerosol sample transformation. Also losses caused by different mechanisms will affect the final measurement result. Therefore the final measurement result is affected by 1) stack aerosol properties, 2) sample transformation in sampling system and transfer lines and 3) measuring device capabilities.

2 SYSTEM DESCRIPTION

2.1 Electrical Low Pressure Impactor ELPI

ELPI is a real-time device for particle concentration and size distribution measurement. It consists of a corona charger, 13-stage low-pressure cascade impactor with isolated stages and multi-channel electrometer measuring the electrical current collected to each impactor stage. Operation diagram of the ELPI is seen in Fig. 1

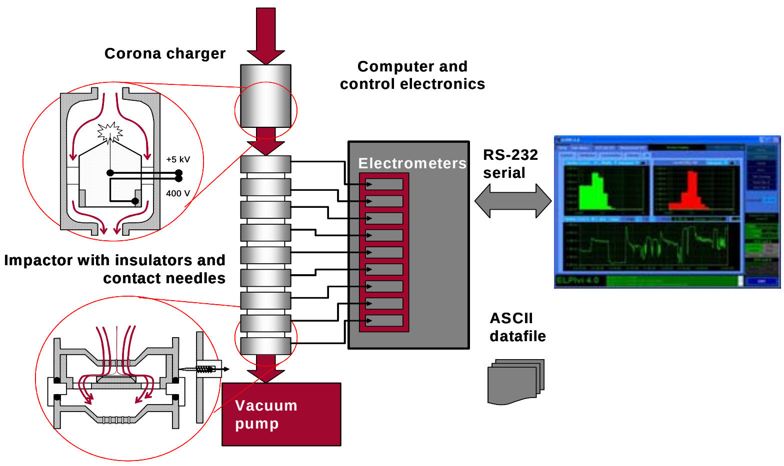

Fig. 1 ELPI operation principle

The ELPI measures particle size distribution at 1 Hz interval. Size range is from 30 nanometers up to 10 microns and it can be expanded down to 7 nm with an additional backup filter stage. Concentration range depends on the particle size but for example for 100 nm particles it is from about 30 #/cm3 up to 3*106 #/cm3 or in terms of mass from about 0.035 µg/m^3 up to 3.5 mg/m^3, respectively.

Since the ELPI size classification principle is inertial impaction, totally separated from particle charging it can be used for size-selective particle charge measurement by switching off the charger. Then current readings from ELPI electrometers are a result of particles natural charge.

2.2 Fine Particle Sampler FPS

FPS is a sampling and dilution device with versatile control possibilities over dilution ratio, temperature and other parameters. Its operation is based on an ejector pump where compressed dilution air is used to create sample suction in a conical nozzle. Dilution air flow is kept constant using critical flow control orifices. Sample flow is dependent on the pressure drop across the ejector which is measured by two pressure sensors.

First dilution stage is located before the ejector. Here dilution air is introduced into the sample flow through perforated tube. This dilution air flow is also regulated by critical orifices and in typical combustion application both the dilution air and the perforated tube dilution stage are heated to avoid volatile material condensation.

In a normal power plant setup there is a heated sampling probe in front of the diluter and optionally a cyclone with 2.5 µm cutpoint and isokinetic nozzle. FPS operation principle is seen in Fig. 2.

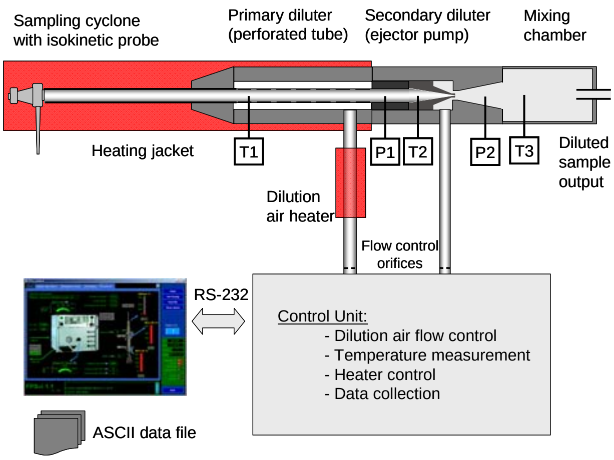

Fig. 2 FPS dilution principle

Dilution ratio of the FPS system can be selected between 1:15 and 1:200, probe and dilution air can be heated up to 400 degrees C or alternatively the first dilution stage can be cooled with water or cold air for nucleation and condensation studies.

3 INSTRUMENT CALIBRATION

3.1 ELPI Calibration

ELPI impactor is calibrated using monodisperse and singly charged particles produced by atomizer and classified by DMA (Differential Mobility Analyser). Selected size class is simply introduced into the ELPI impactor and electrometers connected to impactor stages are used to record where the particles are collected. This method allows simultaneous measurement of impactor collection efficiencies and impactor losses [3].

In the ELPI a specified and size-dependent charging efficiency curve defines the ratio between the measured electrical current from each size class and number of particles in corresponding impactor stage [3]. This calibration is possible since the charge level produced by the ELPI charger remains known and constant.

3.2 FPS Calibration

Fine Particle Sampler is calibrated using accurate laminar flow meters. First of all, each flow control critical orifice is individually calibrated. Then ejector inlet flow is measured as a function of dilution air flow for different ejector diluter inlet pressures. A 2nd order polynomial fit is used to correct the ejector inlet pressure changes to its inlet flow at pressures P1 below 1200 mbar:

$$Q_{ej,in} = \left(A \cdot P1^2 + B \cdot P1 + C\right) \cdot Q_{ej,cal},\ P1 \le 1200$$

This equation takes pressure changes into account, thus separate measurement of the pressure at sampling point is unnecessary.

For pressure $P1$ higher than 1200 mbar, the correction is linear as follows.

$$Q_{ej,in} = \left(D P1 + E\right) \cdot Q_{ej,cal},\ P1 > 1200$$

$P1$ is ejector inlet pressure, $Q_{ej,cal}$ is calibrated ejector inlet flow at standard conditions.

In addition to pressure correction inlet flow is also corrected for ejector inlet temperature $T2$.

Total dilution ratio is calculated as

$$DR_{tot} = DR_{po} \cdot DR_{ej}$$

where dilution ratio of perforated tube, i.e., primary diluter (DR_{po}) is calculated as follows

$$DR_{po} = \frac{Q_{ej,in}}{Q_{sample}} = \frac{Q_{ej,in}}{Q_{ej,in} - Q_{po,dil}}$$

$$\frac{1}{DR_{po}} = 1 - \frac{Q_{po,dil}}{Q_{ej,in}}$$

And the dilution ratio of ejector, i.e. secondary diluter (DR_{ej}) is calibrated and calculated as follows

$$DR_{ej} = \frac{Q_{ej,tot}}{Q_{ej,in}} = \frac{Q_{ej,in} + Q_{ej,dil}}{Q_{ej,in}} = 1 + \frac{Q_{ej,dil}}{Q_{ej,in}}$$

Thus, the total dilution ratio (DRtot) is calculated

$$DR_{tot} = \frac{1 + \dfrac{Q_{ej,dil}}{Q_{ej,in}}}{1 - \dfrac{Q_{po,dil}}{Q_{ej,in}}}$$

3.3 System Losses

Dilution system losses consist of gravitational, inertial and turbulent impaction, isokinetic sampling, thermophoretic, diffusion and electrostatic losses [4]. In the FPS system all these loss mechanisms are minimized:

Main approach in the FPS design was to keep the residence time as low as possible and the sample path through the diluter as straight as possible. Residence time in the heated probe is calculated as 0.1 – 0.8 seconds and in the diluter itself as less than 0.1 seconds. Low residence time minimizes all losses.

Impaction losses in the FPS are prevented by making the sample path straight tube while stainless steel construction minimizes electrostatic losses.

Especially after ESP particles are highly charged, and this will cause space charge losses. These losses have been calculated in [5], and found out to be a function of particle concentration, residence time and size. Since the concentrations after the ESP are typically low the losses are also almost negligible. In [5] the losses have been calculated for 40 and 400 nm particles for ELPI stage 12 having a residence time of 0.14 seconds (comparable to FPS residence time) and found out to be between 0.001% and 2 % for concentrations between 1 e^4 and 1.5e^7 #/cm^3 and total losses (diffusion, space charge and image charge) between 0.9 and 2.7%. At low concentrations (1 e^4 #/cm^3) the main loss mechanism is diffusion (97%–99.8% of all losses for 400 nm and 40 nm particles).

Thermophoretic losses are prevented by heating the sampling probe to same or higher temperature than sample temperature. Sample cooling occurs very quickly in the ejector diluter where the flow is coaxial; once diluted hot sample in the middle, cold dilution air surrounding it. After dilution a very quick mixing happens in the mixing chamber.

Sampling cyclone nozzle is provided in different sizes, allowing isokinetic sampling from different flows. However the FPS inlet flow is usually kept constant, therefore isokinetic sampling requires constant flow velocity in the stack as well as separate stack flow velocity measurement.

Sampling cyclone cutpoint is measured as a function of sampling flow rate and the result is seen in Fig. 3: D50% is between 2.4 and 5.0 microns at sample flow rates 5.4 l pm – 8.9 l pm.

Since the largest particles are removed from the sample flow and the residence times are short enough the gravitational settling can be ignored.

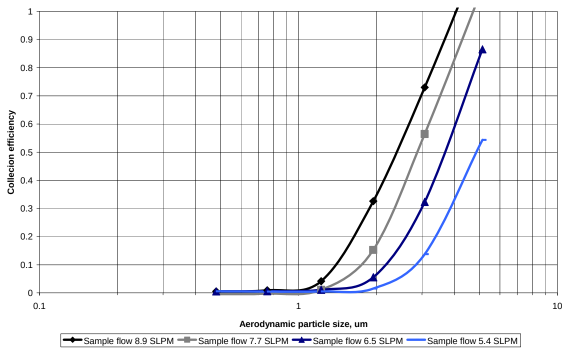

Fig. 3 cyclone collection efficiency at different flow rates

4 DILUTION SYSTEM EFFECTS ON PARTICLE CHARGE

In general diluted sample should represent stack conditions as closely as possible. However temperature decrease and volatile material behavior during dilution process might change particle mass / charge ratio. If particle size changes after the ESP due to volatile material condensation or evaporation the particle charge remains the same but volume and active surface area changes. Therefore sampling conditions and sampling temperature profile must be selected so that the temperature change is known and well controlled.

4.1 Instrument Setup at Power Plant

An ELPI – FPS system has been installed at several power plants. Robustness has been proven at harsh environments, even at -25 ºC temperature. FPS has been used for several days without need for cleaning, also proving that the losses in the system are very low.

Power and dilution air consumption of the system is as follows:

Table 1 Power consumption requirements

ELPI	250 W
Vacuum pump	750 W
FPS	2000 W
Dilution air	200 lpm, 4.5 bar
Total	3000 W 200 lpm @ 4.5 bar

Weight of the system is 125 kg and the whole system can be installed into a 19" rack.

Concentration and Size distribution measurement

Actual measurement data has been collected during the EU project CEMPM Craft in Martinlaakso Power Plant, Vantaa, Finland in January 1004. The 225 MW power plant was operated on pulverized coal combustion process.

A Gothe impactor (TÜV) and Electrical Low Pressure Impactor measured mass concentration for smaller particle sizes, i.e. PM2.5 and PM10. In addition to the mass results, ELPI monitored the continuous size distribution and particle number concentration in the size range of 0.030 µm–10 µm.

In the following, the results of ELPI are presented. They are also shown in comparison to the Gothe impactor results.

The Martinlaakso power plant is equipped with Fläkt FAA-3×37, 5-81115-2 ESP, baghouse filter and wet scrubber with desulphurization. A variation to the plant operation in terms of particle concentration was achieved as the flue gas was directed to bypass the desulphurization process. The alteration in the flue gas treatment enabled measurements of ca. 50 times–70 times higher concentrations compared to normal operation.

4.2 Measurement Setup

The sample was taken through a heated probe, the tip locating ca. 0.5 meters from the stack wall. In order to prevent condensation the probe temperature was adjusted to be always higher than the temperature of flue gas. From the probe the sample is taken to a Fine Particle Sampler (FPS) for dilution. After a two-stage dilution (first heated, second in the ambient temperature) the sample was measured with an ELPI.

Fig. 4 represents the measurement setup including ELPI-FPS system and Gothe impactor.

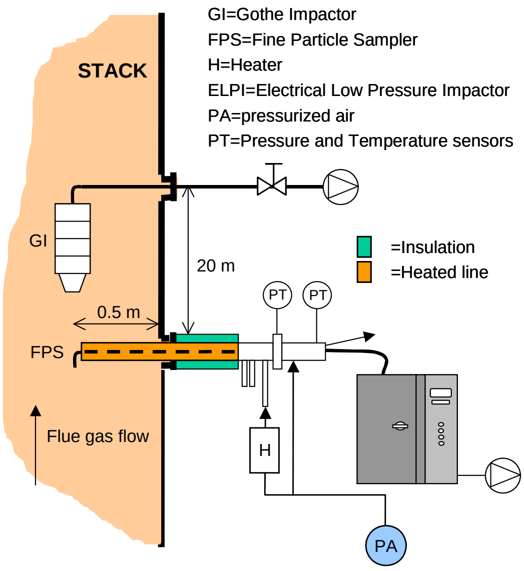

Fig. 4 Measurement setup at power plant

5 RESULTS

When the wet scrubber was not in use the sample aerosol was drier than in normal operation and no additional volatilization occurred affecting the gravimetric results. As a consequence, the PM2.5 concentrations measured with ELPI and Gothe impactor parallel, agreed extremely well. All the four measurement results are shown in Fig. 5.

In case of PM10 concentrations the ELPI results showed ca. double the amount of Gothe impactor measurements. This finding is likely due to the high number of ultrafine particles, depositing on the upper stages of ELPI. This is usually corrected in the ELPI calculation but if there is a large amount of particles below ELPI detection limit the correction might not be sufficient.

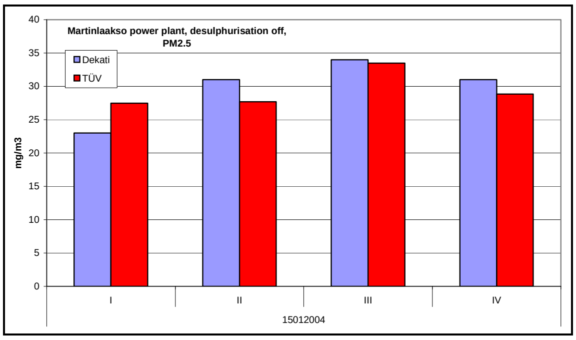

Fig. 5 PM2.5 concentration comparison between ELPI and Goethe impactor, wet scrubber not operational

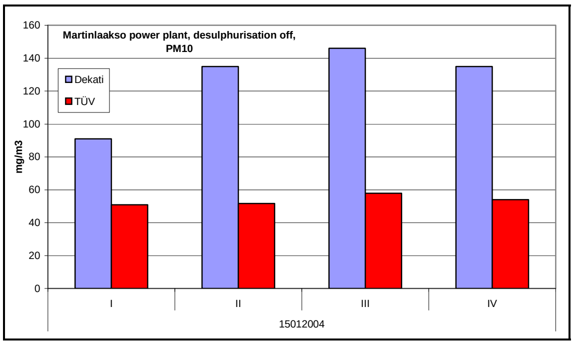

Fig. 6 PM-10 concentration measurement, comparison between Goethe impactor and ELPI, wet scrubber not operational

During the normal operation with wet scrubber and desulphurization PM2.5 concentrations were low (Fig. 7) and on the detection limits of gravimetric method. The zero result for the measurement II is an indication of this.

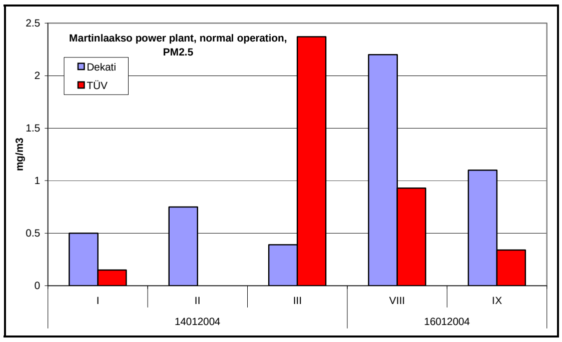

Fig. 7 ELPI and Goethe impactor comparison for PM2.5 during power plant normal operation

It also appears that during the normal operation some volatile material exist in the sample. With the gravimetric method considerable portion of the volatile species are removed due to the equilibration procedure i.e. temperature and humidity conditioning prior weighing. Simultaneously, ELPI detects the total mass concentration including the volatile components.

Normally the sample treatment in the FPS prevents condensation. However in these measurements the FPS temperatures were set only to about 120 degrees C and this was not enough to remove all moisture from particles after wet scrubber.

Measurement III result is also distorted by somewhat different timing. Ca. 10 minutes after the measurement III the power plant was operated bypassing the desulphurization process, which increased the gravimetric mass concentration. This incident is shown in real-time ELPI data in Fig. 8.

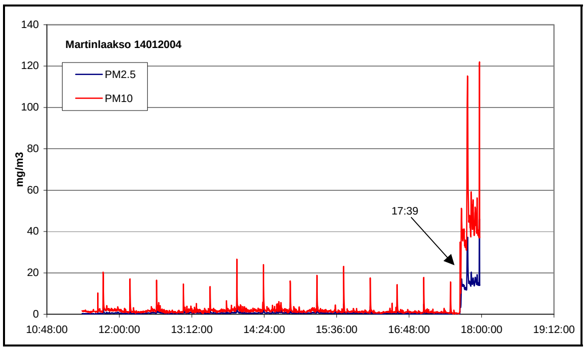

Fig. 8 Real-time data from ELPI shows how the PM2.5 concentration increases during desulphurization bypass

Size distribution Measurement

Both number and mass weighted size distributions were measured in real time during the measurements. Here are presented results with desulphurization on (Fig. 9 above) and off (Fig. 9 below). A clear change is seen in particle size. On one hand mass–based size distribution shows that the particle size decreases when scrubber is used since the wet scrubber removes large particles effectively. On the other hand number-based distribution shows clear decrease for the particle size when scrubber is off – this is due to scrubber's tendency to increase smallest particle sizes due to condensation.

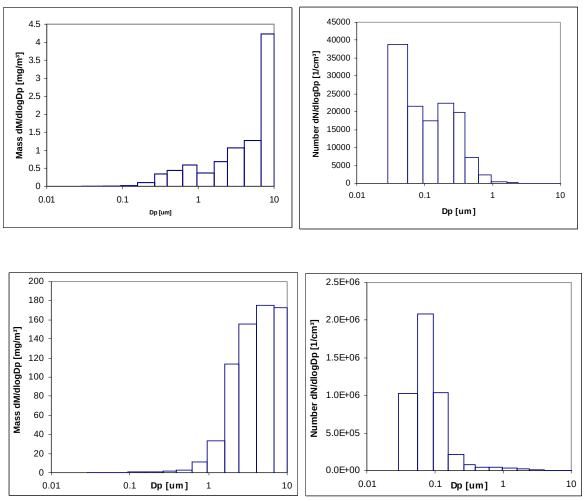

Fig 9 Effect of desulphurization on ELPI mass and number weighted size distributions

Charge Measurements

As the measurement method of ELPI is based on charge detection, it may also be used to measure natural charge distribution of particles. The current is measured when the charger is turned on and off. These readings are seen in Fig. 10.

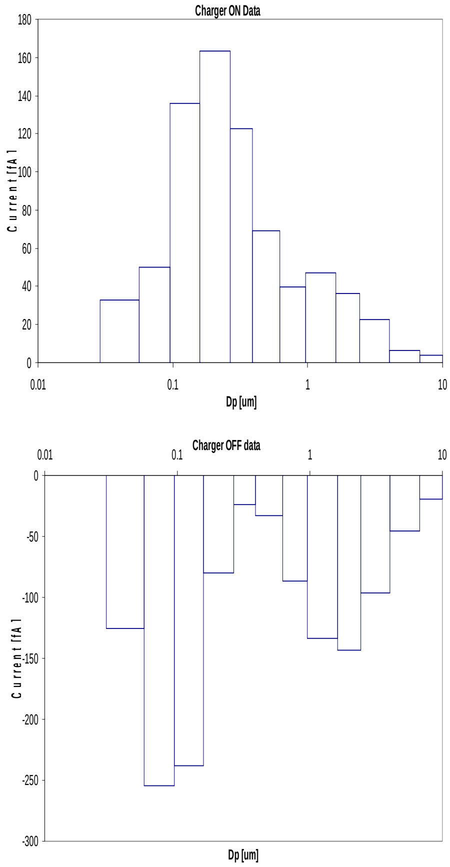

Fig. 10 Current distribution of particles after ESP with charger on (left) and charger off (right)

By combining these data it is possible to calculate ESP charging efficiency for different particle sizes.

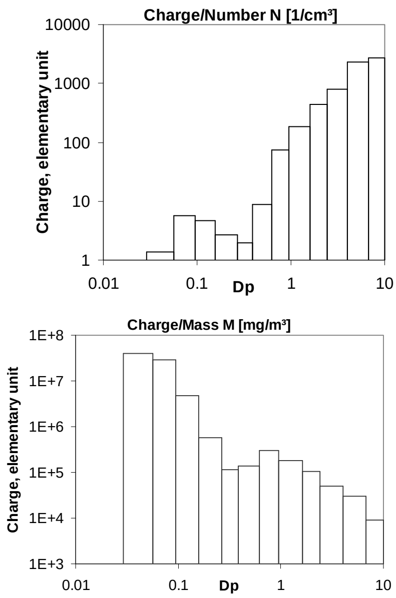

Fig. 11 Charge levels after ESP, charge elementary units / number on left, elementary units / mass [mg] on right. Actual charge is negative but here are absolute values due to logarithmic scale

6 CONCLUSIONS

Electrical Low Pressure Impactor ELPI and Fine Particle sampler FPS form a complete and advanced measurement system for fine particle emission measurements from power plants. FPS dilution system allows sampling from hot flue gas and provides controlled temperature decrease with minimal losses.

Comparison measurements at power plant show that the real-time data allows easy evaluation of the power plant cleaning systems.

PM-2.5 mass concentration comparison show that the ELPI measurement result is comparable to gravimetric measurement but the ELPI tends to overestimate the PM-10 mass concentration. Also it was seen that the sensitivity of the ELPI is better than in gravimetric measurement. Different sampling systems can result to different treatment of volatile material and this can make the comparisons difficult.

By switching the ELPI charger off it is also possible to evaluate the particle charging process in the ESP and calculate the charge / number or charge / mass ratios for different particle sizes.

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