FLUE GASES POLLUTANT CHARACTERIZATION BY MULTISPECTRAL EXTINCTION MEASUREMENT

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ABSTRACT

We present preliminary experimental results relevant to tests carried out on an innovative instrument properly designed for real time measurement of both particle size distribution and concentration in particle laden flows. The system performs on line, continuous, in situ measurements. The instrument, which is based on a multi-wavelength (300nm – 900nm) extinction technique, provides measurements over long optical paths (10m), in the 0.1µm - 3µm diameter range. Precise concentration measurement are guaranteed also in the presence of changes in the particle size distribution due to power load modification and fuel type variations. Preliminary tests have been performed on a thermoelectric fossil fired power plant in Northern Italy. The measured concentrations are in good agreement with the data provided by reference techniques. It is worth noticing that the measured extinction spectrum can also be used to get information about chemical species present in the flue gases. This indicates the possibility of designing a single instrument able to perform both particle and pollutant gases monitoring.

1 INTRODUCTION

Particulate pollution can be produced by many sources, most of them related to combustion processes (automotive, heating, power production, chemical industries, etc.). Particle emissions from thermoelectric power plants are continuously monitored with instruments (opacimeters) directly mounted on the flue gases duct. It is well known that monitoring systems like the commonly used opacimeters can provide information about the amount of solid emissions only if a particulate distribution is assumed, or, in an equivalent way, if a calibration procedure requiring sampling and analysis of the particulate matter is performed.
An optical technique capable of overcoming the above mentioned limitations and recovering both the size distribution and concentration of particulate, is based on the spectral extinction method [1]. This technique is based on the measurement of the extinction coefficient spectrum (i.e. the extinction coefficient measured as a function of the illuminating wavelength) due to particles suspended in flue gases, the size distribution and particle concentration being determined via a properly developed inversion algorithm. Examples of applications of such techniques can be found in the literature [2, 9].
The measurement of the extinction coefficient can be carried out by shining a white light beam and detecting the spectrum of the transmitted radiation after propagation. By comparing this spectrum with the one obtained in absence of particulate, it is possible to determine the spectral extinction coefficient due to the particles suspended along the optical path.
In this work we present a new instrument capable of carrying out semi-automated almost real-time (~ 10s delay) spectral extinction measurements over optical paths of a few meters.

2 THE SPECTRAL EXTINCTION TECHNIQUE

Spectral extinction techniques are based on the measurement of the extinction coefficient α at different wavelengths λ. $\alpha(\lambda)$ is defined by the relation:

$$P_T = P_0 \, e^{-\alpha(\lambda) d} \qquad (1)$$

which is known as the Beer-Lambert law [10]. Equation (1) describes the attenuation of a monochromatic beam of light crossing a sample of length d. P_0 and P_T denote the incident and transmitted power respectively, and (1) is valid only for samples where multiple scattering can be neglected.
The experimental measurement of $\alpha(\lambda)$ is carried out by first determining $P_0(\lambda)$, i.e. the spectrum of the transmitted power with no particles along the optical path. Since the sample cannot be removed from the optical path, no direct determination of the incident power is possible. In this case, the measurements of P_0 and P_T are carried out over two optical paths of different lengths, d_0 and d_1, respectively. Provided that the emission spectrum of the source does not

change during the two measurements, and that there are no distortions on the transmitted spectrum (due to the different layouts of the two optical paths), P_0 and P_T are still related by Eq. (1) where $d = d_1 - d_0$. Thus $\alpha(\lambda)$ represents the mean extinction coefficient averaged over d.
Let us suppose that the sample is a dilute suspension of particles of different sizes, thus, the spectral extinction coefficient is given by:

$$\alpha(\lambda) = \int \pi r^2 Q_{ext}(r, \lambda', m) N(r) dr \qquad (2)$$

where N(r) is the number concentration of particles with radius ranging between r and r+ dr and Q_{ext} is known as extinction efficiency and is given by the Mie theory [10]. Here λ' is the wavelength of the radiation in the medium, and m is the refractive index of the particles relative to the medium. Eq. (2) is a first-kind Fredholm integral equation where $\alpha(\lambda)$ is provided by the experiment, $\pi r^2 Q_{ext}$ is the known kernel and N(r) is the distribution to be recovered. As known, this is a typical example of an ill-posed problem, which means that different distributions can fit the data $\alpha(\lambda)$ with the same level of accuracy, when some noise is present on the data [11]. Therefore, the inversion of Eq. (2) is not a trivial task, and has to be carried out by using stable and reliable algorithms. In this work the inversion of Eq. (2) was carried out by using the non linear iterative algorithm reported and described in Ref. [12].

3 EXPERIMENTAL SETUP

The system is made by two units (the transmitting and the receiving heads), as shown in fig. 1.
The white light source operates with a 150W halogen lamp. The light is spatially filtered and fed to an off axis parabolic mirror that creates a quasi collimated white light beam. The beam crosses the 3.5m flue duct, then it is collected and focused by a second off axis parabola inside an integrating sphere which brings the light to a spectrometer via an optical fiber bundle. This single path configuration can be transformed into a folded path geometry to increase the instrument sensitivity. The spectrum was accurately detected in the spectral region 0.3µm- 0.9µm, with a resolution of ~ 4nm. The instrument performances (sensitivity, accuracy and reliability) were estimated experimentally. The instrument sensitivity, i.e. the minimum detectable extinction coefficient, is $\alpha_{min} \sim 10^{-5}\,cm^{-1}$ for an optical path of 10 m. This value is much smaller than the one expected for aerosols released as a product of combustion processes in industrial plants and is compliant with the limits imposed by the European Economic Community (EEC) regulations [13].

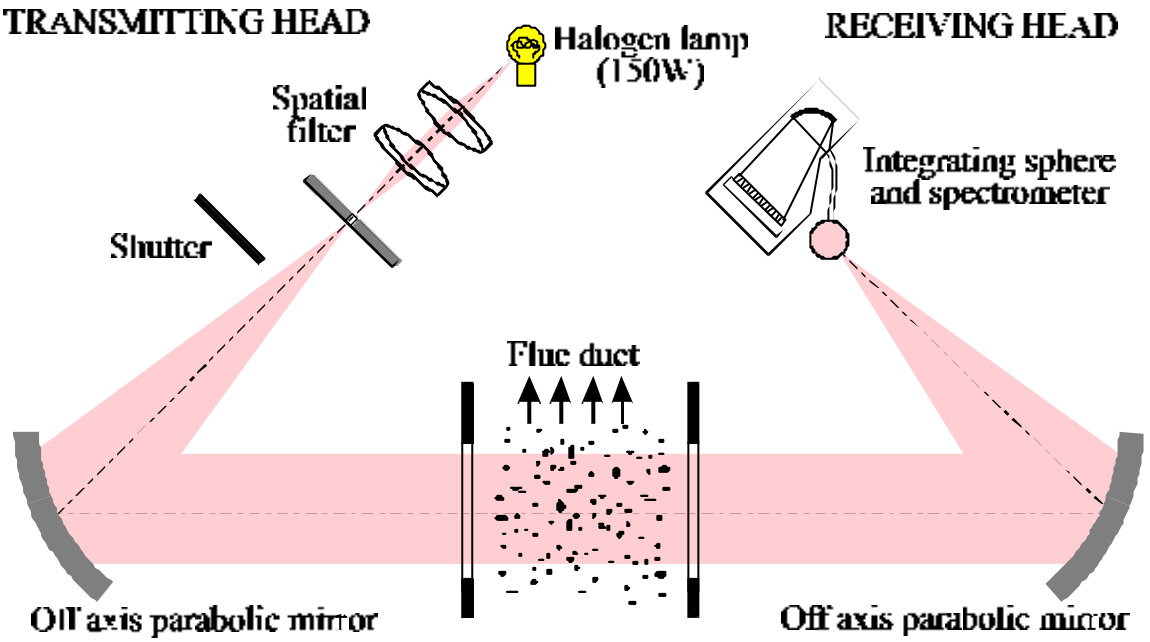

Fig. 1 Optical setup

The experimental activity has been carried out on a thermoelectric power plant (composed by four 320MW groups). The measurements have been performed on a group working at the following operating conditions:

- Load: variable between 300MW and 320MW
- Fuel: 100% natural gas

The two heads of the instruments are shown in fig. 2a, 2b (the photo has been recorded during preliminary tests performed in the laboratory).

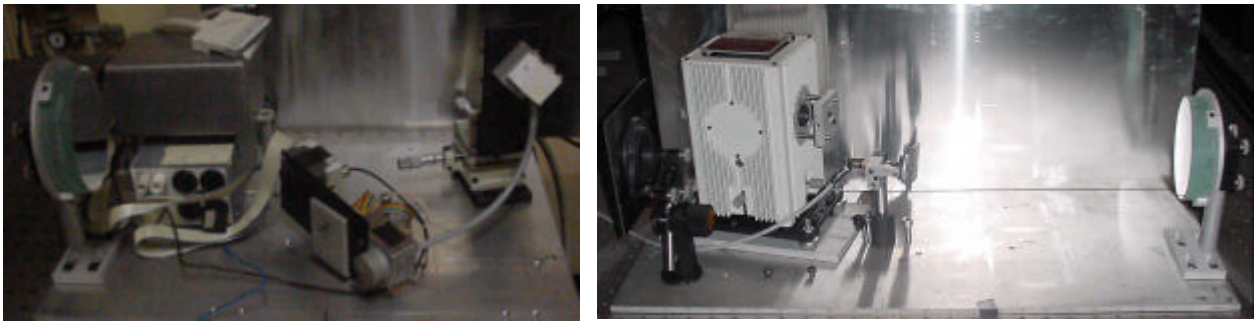

Fig. 2a, 2b Instrument prototype in laboratory: receiving head (left), transmitting head (right)

To install the instrument on the flue duct, two opposite accesses were used. To avoid dust deposition, the optical windows were kept recessed of about 0.5m from the duct and blown by a purging air flow. The dimension of the optical accesses is quite small (50mm) and comparable with the one utilized for the opacimeters.
The instrument was mounted on a duct located just before the electrostatic filter (fig. 3a, 3b). Two metallic shields were used to protect the units.

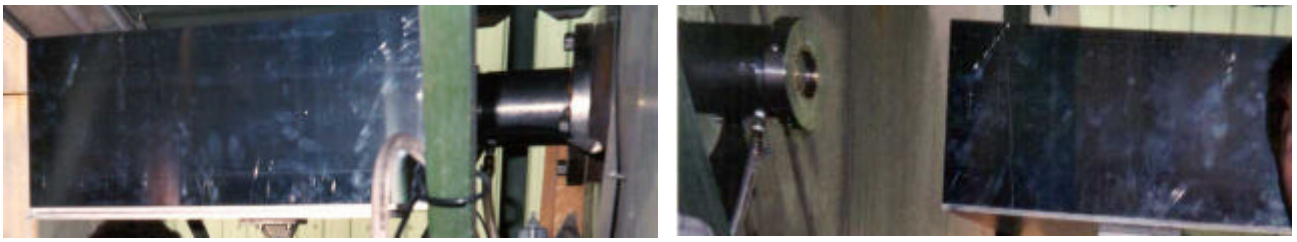

Fig. 3a, 3b The two heads installed on the duct: receiving head (left), transmitting head (right)

4 RESULTS

A series of curves representing the changes in the spectral transmission of the particle laden flow streaming through the duct is reported in figure 4. The curves refer to raw data (windows attenuation is included) obtained at different hours of the day. As one can notice, experimental spectra exhibit appreciable changes in the spectral extinction as a function of time (this is probably due to changes in the particle size distribution). This means that the use of single wavelength extinction measurements (like those performed by opacimeters) can be questionable, since these techniques provide results that strongly depend on the selected wavelength.

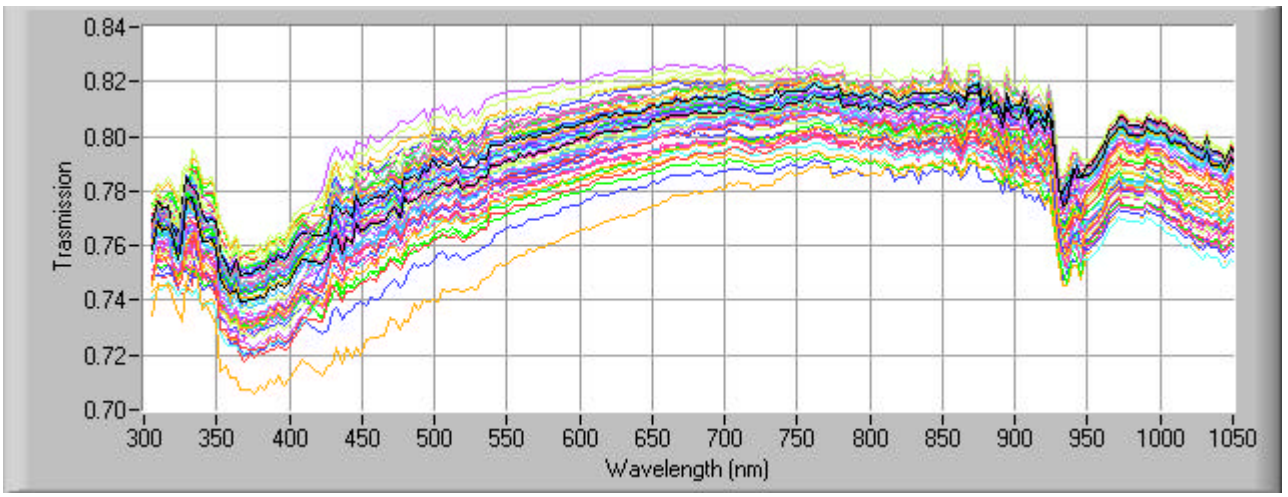

Fig. 4 The spectral extinction measured at different hours of the day (windows attenuation included)

The spectrometer also provides, with a lower accuracy, the spectrum beyond 900nm. These transmission spectra have been determined by normalizing the measured spectrum to a reference spectrum obtained in the laboratory in the absence of particles, utilizing a similar optical configuration. By skipping the data relevant to gases absorption lines and by using a fitting procedure it is possible to reconstruct the spectral transmission curve produced by the particulate (fig. 5).

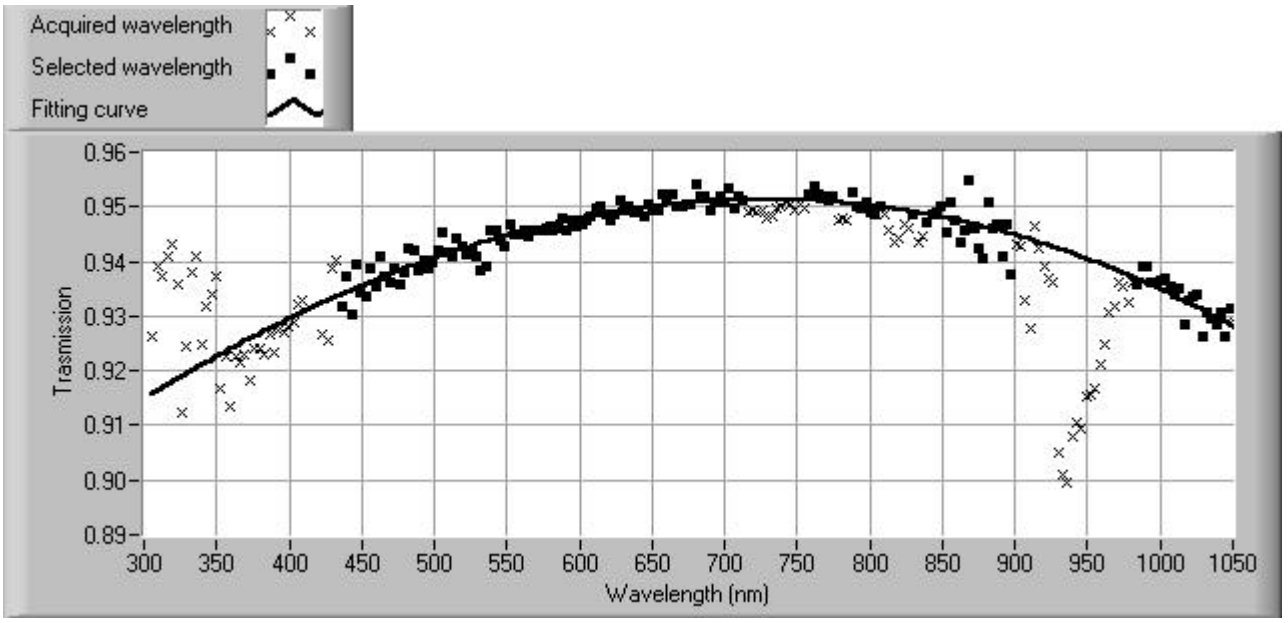

Fig. 5 Reconstruction of the particulate transmission curve

From the transmission curves it is now possible to calculate the particulate extinction spectra. By inverting the spectral extinction with a proper inversion algorithm it is possible to derive both the particle size distribution and the particle concentration (an example is reported in fig. 6).

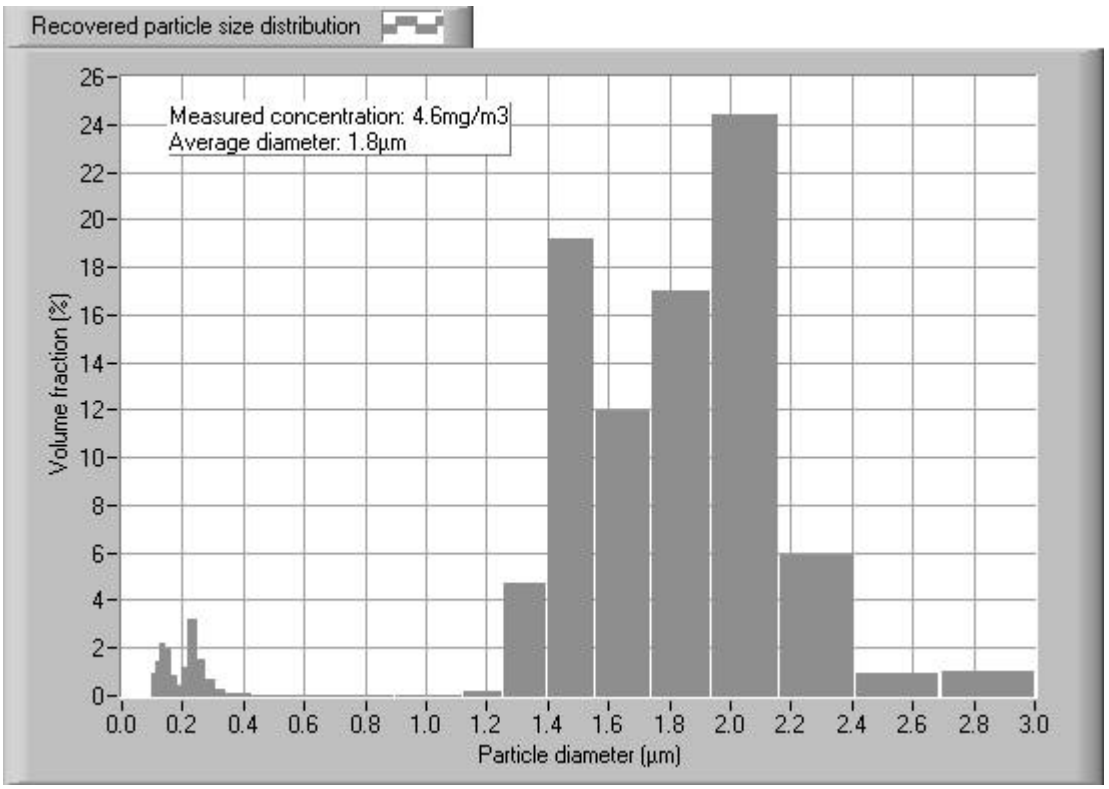

Fig. 6 Reconstructed particle size distribution

As it can be noticed, this curve shows two different sets of particles with different size. The smaller particles are probably soot while the presence of the larger particles can be explained by the fact that the group was fed by oil few days before our measurements. It is well known in fact that, when changing from oil to gas fuel, it takes few weeks before the ducts become completely cleaned from the particle released during the oil combustion.
Figure 7 shows the comparison between the experimental spectral extinction data (dots) and the spectral extinction (line) calculated through the recovered particle size distribution shown in fig. 6. As one can notice, the fit between the two curves is quite good.

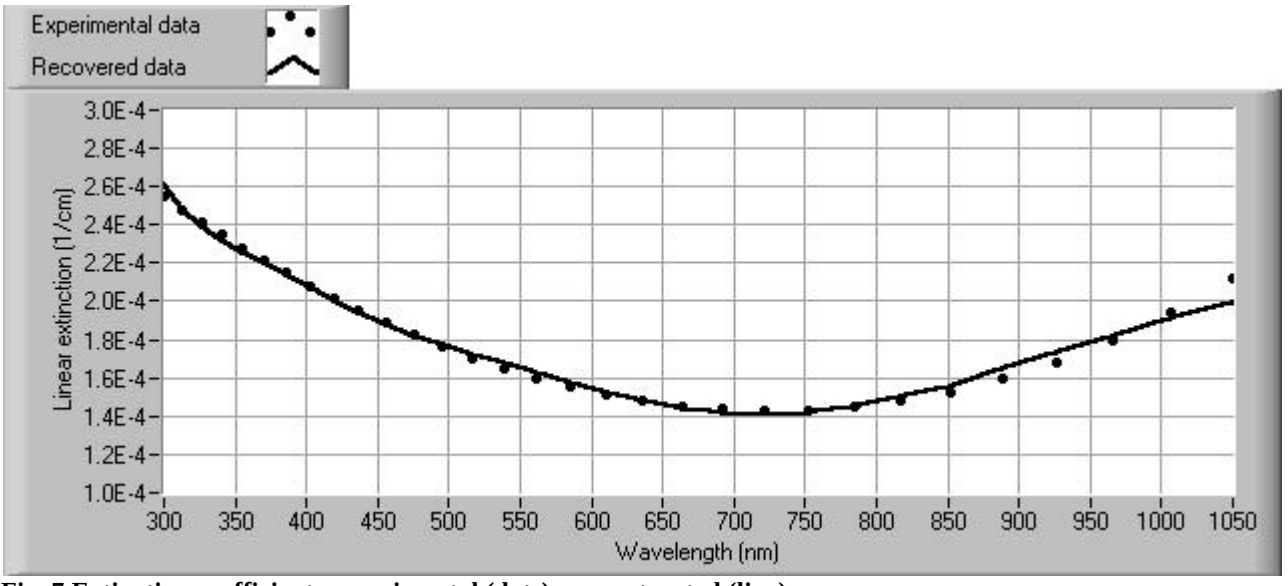

Fig. 7 Extinction coefficient: experimental (dots), reconstructed (line)

Fig. 8 shows the measured concentration, the opacity signal (reported in arbitrary unit) obtained from a conventional opacimeter mounted on the same duct, and the concentration measured by a conventional opacimeter mounted downstream the electrostatic precipitators. The recovered concentration (circles) was obtained by utilizing a three point moving average filtering procedure. Data in fact have been collected over a short lap of time (few seconds about every minute) and this caused the experimental points to be spread in a significant way because of the fast particle concentration fluctuations inside the duct.

It is worth noticing that in spite of the almost constant signal obtained from the opacimeters the concentration recovered from the multispectral extinction measurement system reveals a positive trend in the measured concentration. The particle density used for the calculations was $2.7 g/cm^3$.

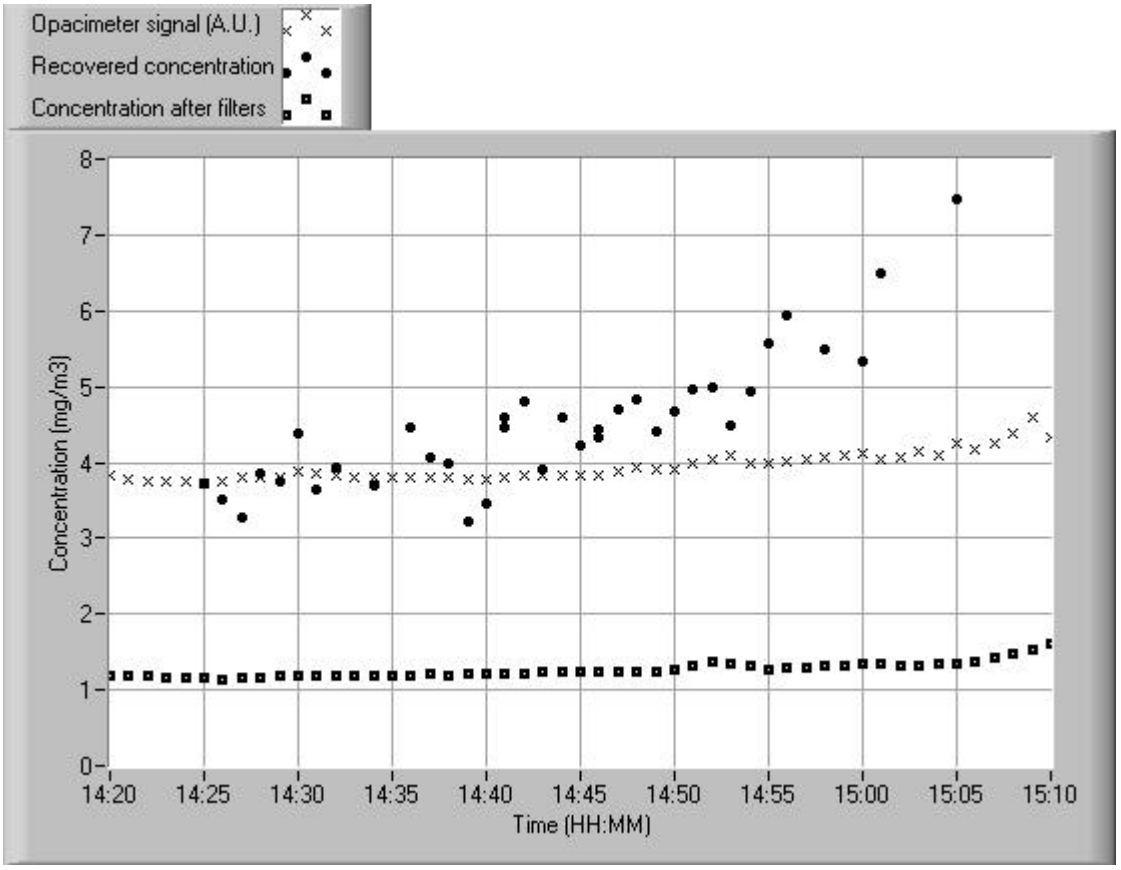

Fig. 8 Concentration measured over 40 minutes (circles), opacity signal (in arbitrary units) from an opacimeter mounted on the same duct (crosses), concentration measured by an opacimeter mounted after the electrostatic filters (squares). Circles are not equally spaced in time because data acquisition was manually controlled (the time scale resolution of this graph is one minute).

The average value of the measured concentration is in good agreement with the one obtained by standard pick up procedure, in fact the particle concentration upstream the electrostatic precipitators is usually few mg/m^3 when the plant is running at the same load conditions using 100% natural gas.
In fig. 9 we show the recorded average diameter for the large particles, (contribution of the small soot particles have not been considered).

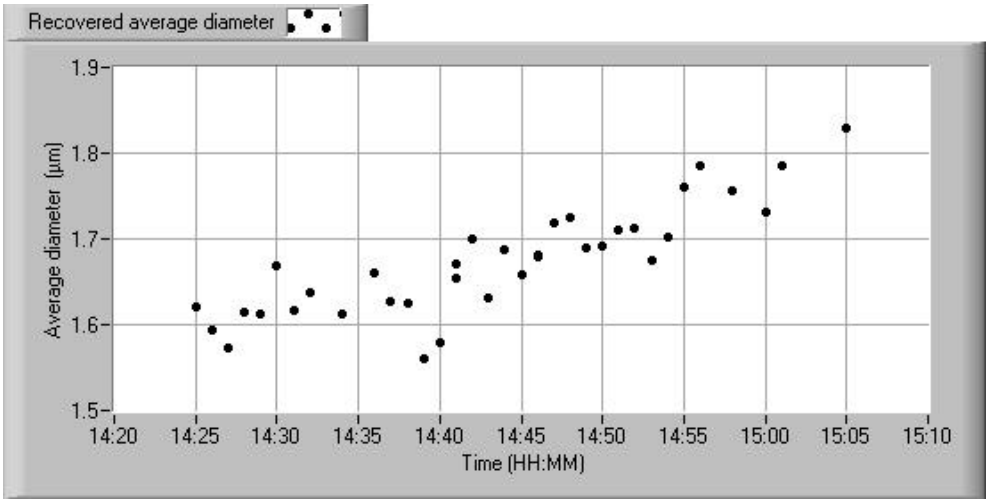

Fig. 9 Recovered average particle diameter

5 CONCLUSIONS

The prototype of a multiwavelength extinction based optical particle sizer for flue gases characterization have been tested on a fossil fired power plant. The instrument, which operates in the size range 0.1µm - 3µm, is capable of performing a broadband 300nm – 900nm spectral extinction measurement with a resolution of few nanometres and a sensitivity on the calculated extinction coefficient of 10^{-5} cm^{-1}. Measurements show that the recovered particle concentrations are in good agreement with the data obtained with standard procedures.

It is worth noticing that from the measured extinction spectrum it is in principle possible to determine the concentrations of some chemical species such as water (930nm) and oxygen (780nm), by measuring their absorption lines.

A further improvement under study is the extension of the particle size range to larger particles, by using recently commercially available spectrometers with larger bandwidth and higher resolution. This will also allow for the use of the instrument to detect the absorption lines of gas species like NO (220nm), SO_2 (290nm) and NO2 (400nm – 420nm).

Some preliminary tests have demonstrated the feasibility of an instrument capable of performing real time, on line in situ measurement of both particle size distribution and gas species in flue gases.

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- Multiwavelength light extinction measurement.
- Optical telemetry.
- Laser Doppler velocimetry.