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Thermo Scientific Hybrid PM CEMS Development Update

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- PM CEMS
- Particulate
- Cement
- Boiler
- Utility
- EGU
- MACT

Introduction

Particulate matter (PM) in the flue gas can exhibit highly variable and dynamic characteristics that are dependent on the plant fuels, processes and control parameters. The main characteristics of interest are mass concentration, particle size, defined by the aerodynamic diameter of the particle, and chemical composition, which relates to the eventual toxicity of the particulate matter in the ambient air outside the stack.

During the past one year, the U.S. EPA has promulgated or proposed three major MACT rules – Portland Cement MACT, Industrial Boiler MACT and Utility MACT – requiring many plants in affected industries to continuously measure the emissions concentrations of particulate matter in the stack gas using continuous emissions monitoring systems (CEMS). This is a departure from previous regulations where opacity monitors were allowed as a surrogate for PM emissions.

Common methods of measuring particulate matter include beta attenuation, light-scattering (forward and backward), light extinction (opacity) and inertial microbalance. The Thermo Scientific Hybrid PM CEMS, currently at a developmental stage, uses a unique hybrid technology that combines desirable characteristics of the light-scattering and inertial microbalance methods to determine the precise concentration of particulate matter. This document shall discuss the motivation behind the choice of the hybrid technology over the others. Also some early results in the field from a prototype system are presented.

Sensing Technologies

The Hybrid PM CEMS uses two complementary sensing technologies, real-time elastic light-scattering and a semi-continuous Tapered Elemental Oscillating Microbalance (TEOM®). The motive behind choosing this hybrid technology was to combine the fast response times offered by light-scattering (nephelometry) with the direct mass measurements performed by the TEOM monitor. By including both methods in one instrument, it is possible to achieve precise measurements from the nephelometer response and its scheduled calibration against the TEOM monitor which responds directly to mass.

As the nephelometer captures the instantaneous state of the sample volume, it offers a real-time response to changes in particulate concentration. At the same time, the limitation of light-scattering, as it is with other optical methods, is its susceptibility to the natural variability of the optical parameters of the particles in the flue gas, regardless of how well the light-scattering device performs. The TEOM monitor, on the other hand, provides a true mass concentration reading, but is limited by a need for regular filter replacement. Using both techniques in one instrument allows the strengths of one method to offset the weaknesses of the other and ultimately creates potent hybrid measurement capabilities.

Light-scattering (Nephelometry)

Nephelometry is based on the measurement of the irradiance of the light scattered by a collection of particles passing through a sensing volume usually defined by the intersection of the illuminating beam and the field of view of the detection optics. Unlike the case of particle counters, the sensing volume is required to be large with respect to the inverse of the particle number concentration. The resulting signal is linearly proportional to particle volume concentration for an aerosol of constant optical properties (i.e., particle size, shape and refractive index), contingent on satisfying the conditions of independent and single scattering, which are always maintained over the concentration range of interest.

The use of elastic light-scattering in the Hybrid PM CEMS offers two intrinsic advantages. The first advantage is a highly time-resolved measurement that will capture any rapid fluctuations in the flue gas.

The second advantage is realized by the use of measuring at two different scattering angles, which offers insight into the changing characteristics of the particulate from the source. This second advantage assists in driving this hybrid methodology.

The main drawback of the light-scattering method is the threat to repeatable accuracy over a longer period. Although a light-scattering measurement "responds" to particle volume concentration it can only provide accurate measurements if the device has been calibrated to an aerosol of constant optical properties. As a result, the accuracy of the nephelometer is affected by changes in the scattering efficiencies, particle characteristics and scattering phase functions, likely to occur in the flue gas because of dynamic changes in the plant's processes. Therefore, by utilizing an in-line inertial microbalance, the relationship of mass concentration to light-scattering response can be maintained no matter what the change is in aerosol properties.

Inertial Microbalance

The TEOM monitor offers the most direct approach to mass measurement through the measurement of change in resonant frequency due to deposition of particles onto a vibrating surface. The TEOM monitor technique relies upon an exchangeable filter cartridge seated on the end of a hollow tapered tube. The wider end of the tube is fixed. Air is passed through the filter, on which particulate deposit, and the filtered air passes through the tapered tube to a flow controller. The tapered tube with the filter on its end is maintained in oscillation in a clamped-free mode. The frequency of oscillation is dependent upon the physical characteristics of the tapered tube and the mass on its free end. As particulate land on the filter, the filter mass change is detected as a frequency change in the oscillation of the tube. The mass of the particulate is thus determined inertially, i.e. directly. When this mass change is combined with the flow rate through the system, the monitor yields an accurate measurement of the particulate concentration in real time.

The major advantage of this method is that any changes in aerosol characteristics will not influence the accuracy of the mass measurement. In the Hybrid PM CEMS, this internal mass measurement method, traceable to NIST-standards, is used to calibrate the response of the light-scattering nephelometer.

While the TEOM monitor offers a high level of accuracy, it is limited by the useful life of the filter substrate. The filter must be replaced after it has been loaded beyond a threshold that impacts the resonant frequency of the system. In stack conditions with high particulate levels, continuous use of the TEOM monitor can create frequent maintenance needs. Therefore, the filter life can be extended significantly – beyond one month – by utilizing the TEOM monitor on a semi-continuous schedule in the Hybrid PM CEMS.

Light-scattering versus Beta Attenuation

Light-scattering was chosen as the primary measurement method because of its non-intrusive technique and fast response. This choice was made in consideration of the other available alternative, beta attenuation. Beta attenuation is a radiometric technique that exhibits an exponential attenuation characteristic as a function of the mass per unit area interposed between a beta emitting isotope and a detector.

In an ambient monitoring application, beta attenuation can often provide the desired level of accuracy. However, it must be understood that a dependency of the measured mass can be affected by chemical composition (i.e., atomic number-to-atomic weight ratio). Therefore, the choice of calibration standards requires certain precautions be taken to interpret the results from discrete pollution sources accurately. In referencing the widely used periodic tables originated by Dimitri Mendeleev in 1869, the atomic number-to-atomic weight ratio has a direct impact on the mass absorption coefficient used to correct the attenuation results to a mass value. Research was previously completed in 1981 by J.M. Jaklevic, et al[1] ., which demonstrated how particulate composition could influence mass absorption coefficient dependency. This influence is shown in Figure 1 and Table 1. This information led us to believe that the accuracy could not be maintained across all particulate source categories and would likely not meet our acceptable performance standards.

Description of Hybrid PM CEMS

The approach to designing any CEMS includes an understanding of the sample characteristics. Moisture content, as either vapor or condensed droplets, poses the greatest risk to the successful operation of a PM CEMS.

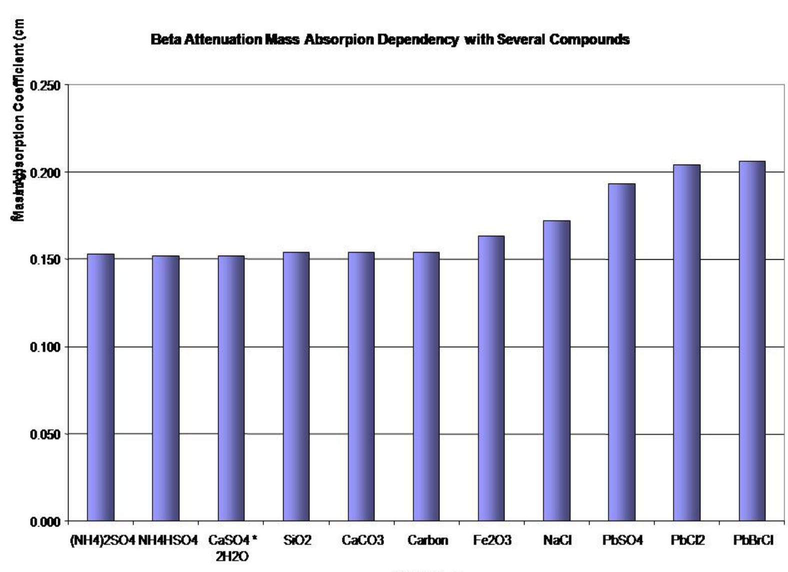

Figure 1: **Beta attenuation Mass Absorption Dependency with several compounds**

Table 1: Effect of Atomic Number Dependence of the Measured Mass of Several Compounds

Effect of Atomic Number Dependence on the Measured Mass of Several Compunds

Compund	Z/A (---)	μ (cm^2/mg)
$(NH_4)_2SO_4$	0.530	0.153
NH_4HSO_4	0.521	0.152
$CaSO_4 * 2H_2O$	0.511	0.152
SiO_2	0.499	0.154
$CaCO_3$	0.500	0.154
Carbon	0.500	0.154
Fe_2O_3	0.476	0.163
NaCl	0.478	0.172
$PbSO_4$	0.429	0.193
$PbCl_2$	0.417	0.204
PbBrCl	0.415	0.206

Notes:
- Z/A: Atomic number to weight ratio
- μ: Mass absoption coefficient for beta attenuation

The second risk is the overall sample transport to the point of measurement. In the Hybrid PM CEMS design, the sample is extracted and immediately mixed with ultra-dry, clean gas to minimize moisture content and allow sample transport to occur under controlled conditions. The final concentration can be calculated by carefully monitoring the dilution ratio.

As seen in Figure 2, the sample gas is drawn from the stack through a fast loop and is finally returned to the flue. A diluted portion of the sample gas is extracted from the fast loop and transported to the light-scattering stage (LSS) where it is analyzed.

The particulate sample may subsequently be collected by a filter during normal operation or delivered to a filter attached to the TEOM monitor for mass measurement during a mass calibration period. In each case, the remaining gas flow is metered and returned to the fast loop. The Hybrid PM CEMS uses a ratio of the TEOM monitor and LSS readings, collected during mass calibration, and the dilution ratio to correct the real-time LSS output to become the final concentration output of the Hybrid PM CEMS.

Discussion of Field Results

We are currently running multiple alpha tests of the Hybrid PM CEMS in the field and are in the process of evaluating early results. We recently installed an alpha prototype system (see Figure 3) at a coal-fired power plant that utilizes an Electro Static Precipitator (ESP) for particulate control followed by a Wet Flue Gas Desulfurization System (FGD) for SO_2 scrubbing. During this test, reference testing was made in accordance with the performance specifications, PS-11. The installation involved a heated probe, a combined probe controller and mass monitoring enclosure, and a clean air panel.

The main objective of this alpha test was to evaluate the performance of the critical sensing functions of the Hybrid PM CEMS, specifically the light-scattering stage, forward-to-back scattering response changes, TEOM stage and probe performance. The system was set up to maintain a heated sample stream with a 16:1 dilution ratio and 2 lpm extraction flow with scheduled blowback. The LSS was continuously operated and included two detectors at independent scattering angles. The TEOM was operated manually.

Figure 2: Functional overview of the Hybrid PM CEMS

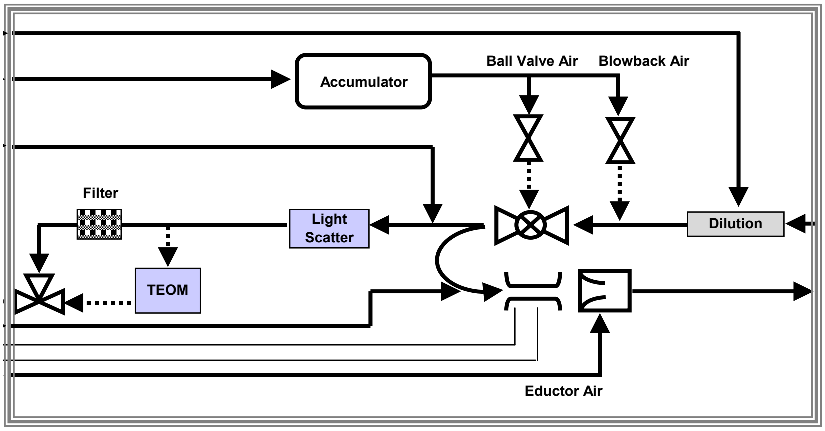

Figure 3: View of the Alpha test installation at a coal-fired plant

Figure 4 shows two light-scattering responses and a calculated ratio of forward-to-back scattering. The sudden drop-out of each signal and ratio is related to the scheduled blowback periods. On this day of testing, it was known that the ESP was being detuned in preparation for forthcoming PS-11 testing. As the detuning process progressed, an increase in both scattering measurements and ratio were observed. However, it can be seen that the increase of forward scattering is disproportionate to the increase in back scattering during this period. The theoretical reason for this phenomenon could be an enhanced light-scattering towards the forward region from an increase in particulate size.

This theory is validated by our knowledge of the process in this example. We know that the first two fields of the ESP were turned off to increase particulate loading. When this occurs the particulate accumulating on the last field will result in larger agglomerates being passed through to the flue. Therefore, the collected data supports the previously stated theory that light-scattering will change in response to changing optical characteristics of the particulate (i.e., size). One of our primary goals for the Hybrid PM CEMS is to provide an accurate representation of changing particulate characteristics as a useful tool for instrumentation data processing and also for facility knowledge.

Figure 4: **LSS scattering responses from Alpha test**

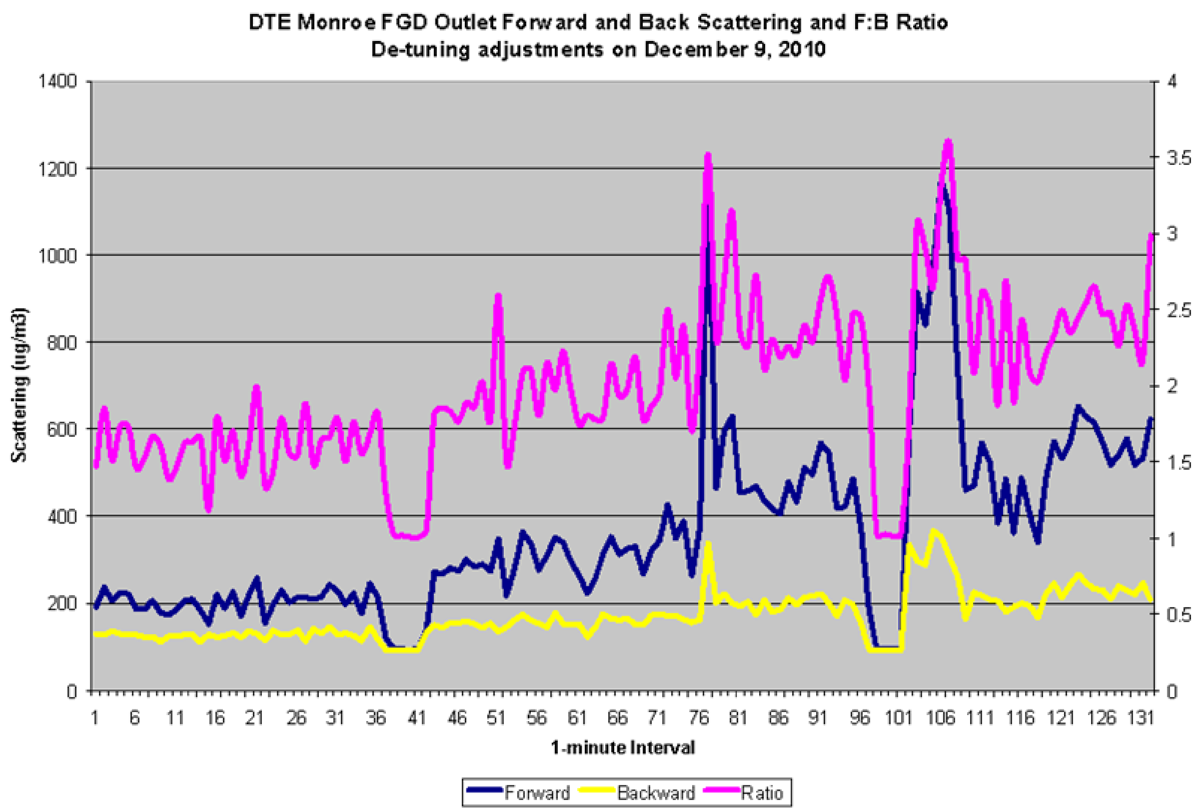

Figure 5: **Plot comparing TEOM and Nephelometer response during mass calibration**

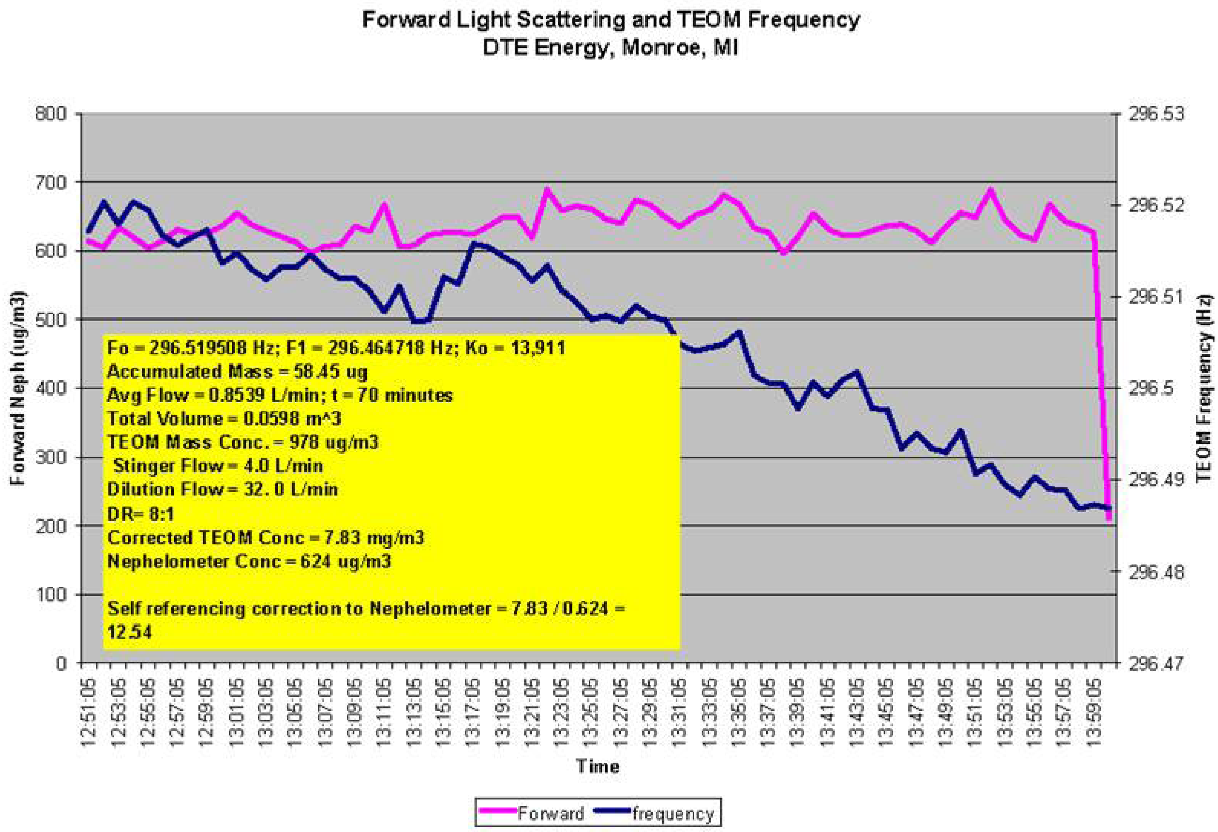

Figure 6: Hybrid PM CEMS calibrated response

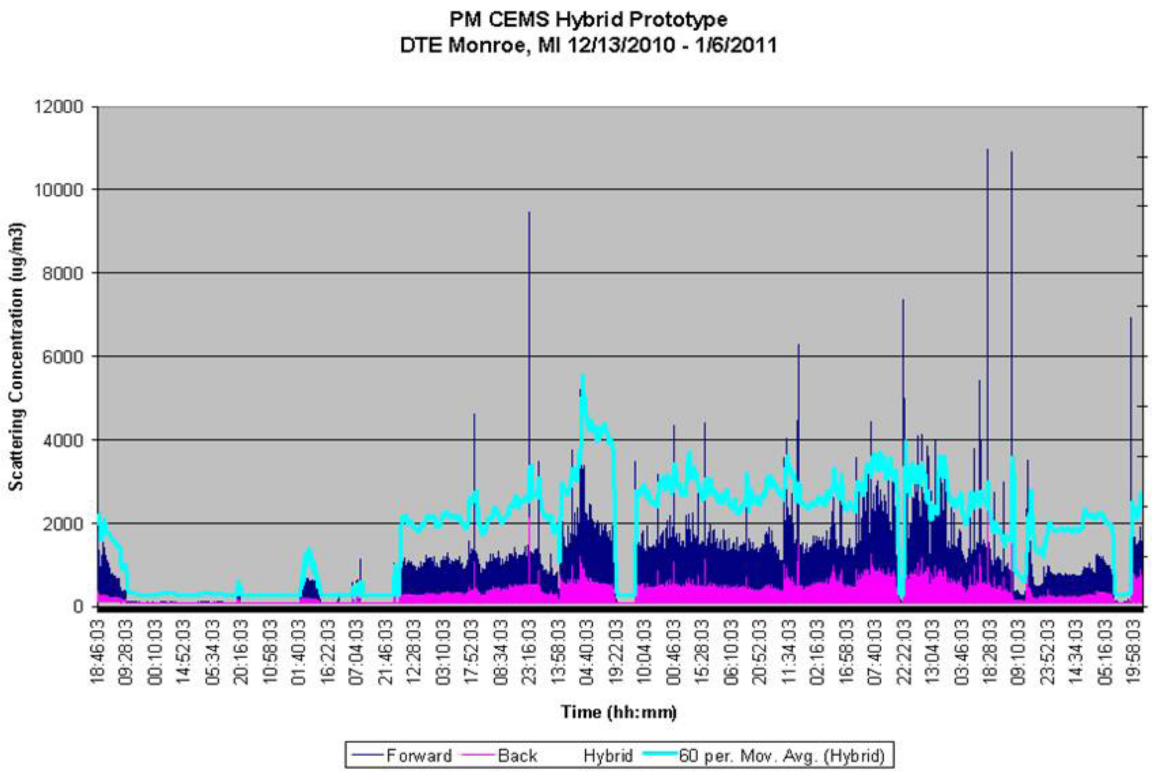

Figure 5 demonstrates the mass calibration period during which the TEOM frequency decreases with particulate loading while the forward scattering channel from the LSS provides a real-time response. By using the average values of each during this synchronized period, a correction factor is calculated and applied to the system to yield a hybrid calibrated response.

As seen in Figure 6, the forward scattering channel is adjusted using the correction factor to generate a calculated hybrid response. At one point in this test, the water coolant inlet screens were blocked by a large school of fish, which caused the facility to shut down for a certain period. Other dips in response are predominantly from other flow outages in the facility and on a minor level the clogging of our prototype nozzle design.

Conclusion

Alpha testing of the Hybrid PM CEMS is reaching its conclusion. Preliminary field results are very promising, showing a strong correlation between the mass concentration readings of the Hybrid PM CEMS and changes in plant parameters or conditions that affect particulate characteristics. Further, the choice of the hybrid technology is being vindicated by a comprehensible change in observed particulate properties due to changes in process conditions at the plant in our alpha tests. The primary goal of subsequent development efforts will be to make the Hybrid PM CEMS render changing particulate characteristics more accurately. Another targeted area of improvement will be to resolve an issue related to clogging of the probe that was observed on some occasions. More field testing will continue in multiple locations, including at cement kilns and industrial boiler stacks, during the beta phase, with a focus on creating a robust monitoring system capable of fast and accurate measurement.

References:

1. Jaklevic, J.M., R.C. Gatti, F.S. Goulding, and B.W. Loo. 1981. A beta gauge method applied to aerosol samples. Environ. Sci. Tech. 15:680-686

In addition to this offices, Thermo Fisher Scientific maintains a network of representative organizations throughout the world.

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