White Paper

Thermo Scientific PM CEMS: A dual-sensing technology

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Key Words

- Particulate Matter
- Continuous Emissions Monitoring Systems
- Nephelometry
- Inertial Microbalance
- TEOM
- Compliance
- Utility MATS

Introduction

Particulate matter (PM) in flue gas can exhibit highly variable and dynamic characteristics depending on fuel type, combustion process and emission control parameters. The primary characteristics of PM are its mass concentration, size, and chemical composition. Its size influences emission transport and inhalation potential, while its chemistry largely defines its toxicity.

In recent years, 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 a continuous emissions monitoring system (CEMS). This is a departure from previous regulations, which allowed opacity monitors to serve 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^{TM} Particulate Matter Continuous Emissions Monitoring System (CEMS) (Figure 1) uses technology that combines desirable characteristics from both the light-scattering and inertial microbalance methods to accurately determine the precise concentration of particulate matter.

Figure 1: (Top) The Thermo Scientific Particulate Matter Probe Controller, Model 3880i. (Bottom) The Probe, which contains the nephelometer and TEOM.

This document shall discuss the motivation behind the choice to use a dual technology method over the others. Results from PS-11 beta testing are presented.

Sensing Technologies

The dual-method PM CEMS uses two complementary sensing technologies: real-time elastic light-scattering and the semi-continuous Thermo Scientific^{TM} Tapered Elemental Oscillating Microbalance (TEOM®). This dual technology method combines 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

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TEOM monitor which responds directly to mass.

Because it captures the instantaneous state of the sample volume, the nephelometer lets users respond in real-time to changes in particulate concentration. The limitation of lightscattering, however, is its susceptibility (which it shares with all other optical analysis methods) to the natural variability of optical parameters of the particles in the flue gas. The TEOM monitor has its own strengths and limitations: it 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 dual measurement capabilities.

Nephelometry

Nephelometry measures the irradiance of the light scattered by a collection of particles passing through a sensing volume – usually the intersection of the illuminating beam and the field of view of the detection optics. Unlike particle counters, the sensing volume must be large in 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 Thermo Scientific PM CEMS offers two intrinsic advantages: the first is a highly time-resolved measurement that will capture any rapid fluctuations in the flue gas. The second 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 for added emissions research.

The main drawback of light-scattering is the loss of repeatable accuracy over longer periods. 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, which are likely to occur in the flue gas because of dynamic changes in the plant’s processes.

By utilizing an in-line inertial micro-balance like TEOM, the relationship of mass concentration to light-scattering response can be maintained regardless of changes in aerosol properties.

Inertial Microbalance

The TEOM monitor offers the most direct approach to mass measurement by measuring changes in resonant frequency caused by the deposition of particulate matter onto a vibrating surface. This technique relies upon an exchangeable filter cartridge seated on the end of a hollow tapered tube. The wider end of the tube is fixed. The particulate matter is deposited on the filter as air is passed through the tube; the filtered air then passes through the tapered tube to a flow controller. The tapered tube with the filter on its end oscillates in a clamped-free mode. The oscillation frequency 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 causes a frequency change in the oscillation of the tube. By combining this mass change data 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 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. The filter life can be extended significantly – beyond one month – by utilizing the TEOM monitor on a semi-continuous schedule in the PM CEMS.

Light-Scattering Versus Beta Attenuation

For the PM CEMS, light-scattering was chosen as the primary measurement method because of it is non-intrusive and offers fast response. This choice was made in consideration of an alternative technology, 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 the measured mass can be affected by chemical composition (i.e., atomic number-to-atomic weight ratio). Therefore, certain precautions must be taken to interpret the results from discrete pollution sources accurately.

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 previously completed in 1981 by J.M. Jaklevic, et al., demonstrated how particulate composition could influence mass absorption coefficient dependency. This influence is shown in Figure 2 and Table 1.

Compound	Z/A	μ (cm²/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

Table 1: Effect of atomic number dependence on the measured mass of several compounds. Z/A is the atomic number to weight ratio. μ is the mass absorption coefficient for beta attenuation.

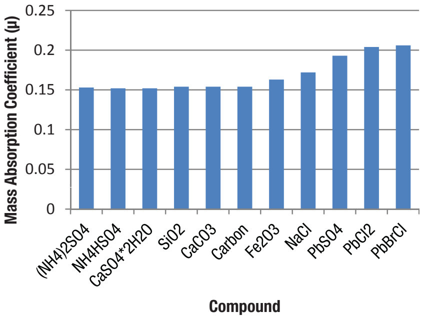


Figure 2: Beta attenuation mass absorption dependency with several compounds.

This information led to the conclusion that accuracy could not be reliably maintained across all particulate source categories and would likely not meet acceptable performance standards.

Description of PM CEMS

One of the most critical parts of the design process of any CEMS is protecting the system against failure. Moisture content, as either vapor or condensed droplets, poses the greatest risk to the successful operation of a PM CEMS. Another risk is overall sample transport to the point of measurement. In the 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 3, the sample gas is drawn from the stack through an in-stack dilution probe. A portion of the diluted sample gas is transported to the nephelometer stage where it is analyzed.

The particulate sample may subsequently be collected by an in-line filter during normal monitoring operation or delivered to a filter attached to the TEOM monitor for a mass calibration period. The Thermo Scientific PM CEMS uses a ratio (PM Factor) of the TEOM monitor and nephelometer readings in conjunction with the dilution ratio to correct the real-time nephelometer output to generate the final concentration output of the PM CEMS. This final concentration is referred to as “PMwet” since it is derived from a dilution measurement.

Discussion of Field Results

The Thermo Scientific PM CEMS has been installed at several coal-fired power plants. These power plants utilize an Electro Static Precipitator (ESP) for primary particulate control, followed by a Wet Flue Gas Desulfurization System (FGD) for SO_2 scrubbing (see figure 4). During this test, reference testing was done 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.

Figure 4: View of the alpha test installation at a coal-fired power plant.

The main objective of these tests was to evaluate the performance of the critical sensing functions of the PM CEMS during PS-11 and

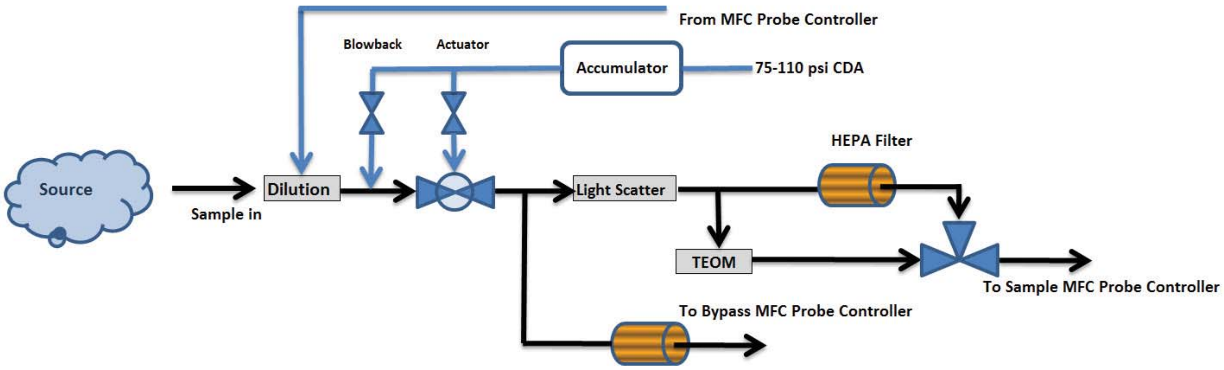


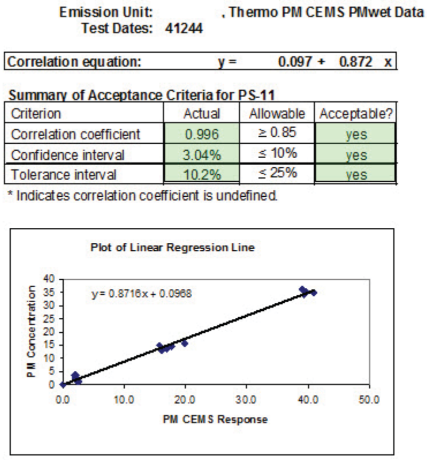
Figure 3: Functional overview of the Hybrid PM CEMS.

Procedure 2 evaluations. Further collocated data was gathered to evaluate the field precision of the PM CEMS. The system was set up to maintain a heated sample stream with an approximate 12:1 dilution ratio and 2 lpm extraction flow with scheduled blowbacks and system checks. The nephelometer was continuously operated. During PS-11 testing the TEOM was operated continuously, and during normal daily monitoring the TEOM was activated once per day for approximately 2 hours.

Figure 5 shows the results of the variation of the PM Factor during a single day of PS-11 testing. Notice the variability in the PM factor. Furthermore, the PM factor varied by 280% during the three days of testing. This variation supports the need for an internal mass reference device (i.e., TEOM).

Figure 6 demonstrates the results of a PS-11 correlation test using the standard US EPA spreadsheet tool. The performance of the Thermo Scientific PM CEMS during these tests clearly meets the US EPA criteria for acceptability. Furthermore, the PM CEMS also meets internal development goals of +/- 20% of the reference method.

Figure 5: LSS scattering responses from Alpha test. PM Factor is updated every 15 minutes. Forward scatter is continuously scaled to TEOM.



Emission Unit: **, Thermo PM CEMS PMwet Data**
Test Dates: **41244**

Correlation equation:	y =	0.097 +	0.872	x

Summary of Acceptance Criteria for PS-11

Criterion	Actual	Allowable	Acceptable?
Correlation coefficient	0.996	≥ 0.85	yes
Confidence interval	3.04%	≤ 10%	yes
Tolerance interval	10.2%	≤ 25%	yes

* Indicates correlation coefficient is undefined.

Figure 6: Summary of PS-11 correlation results.

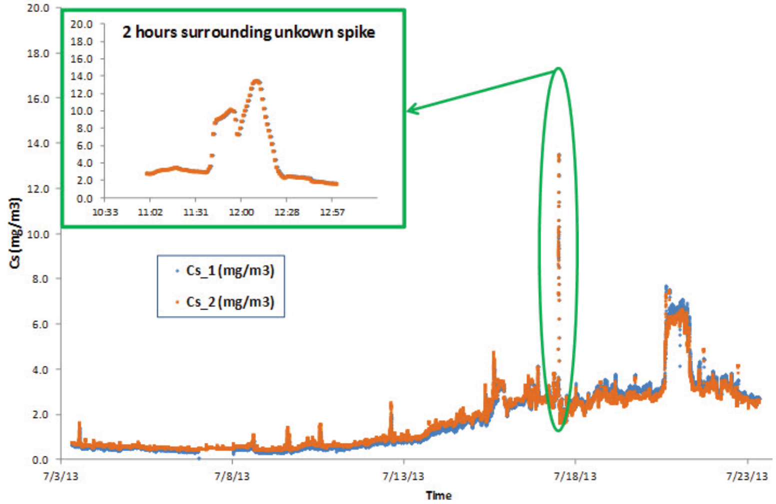
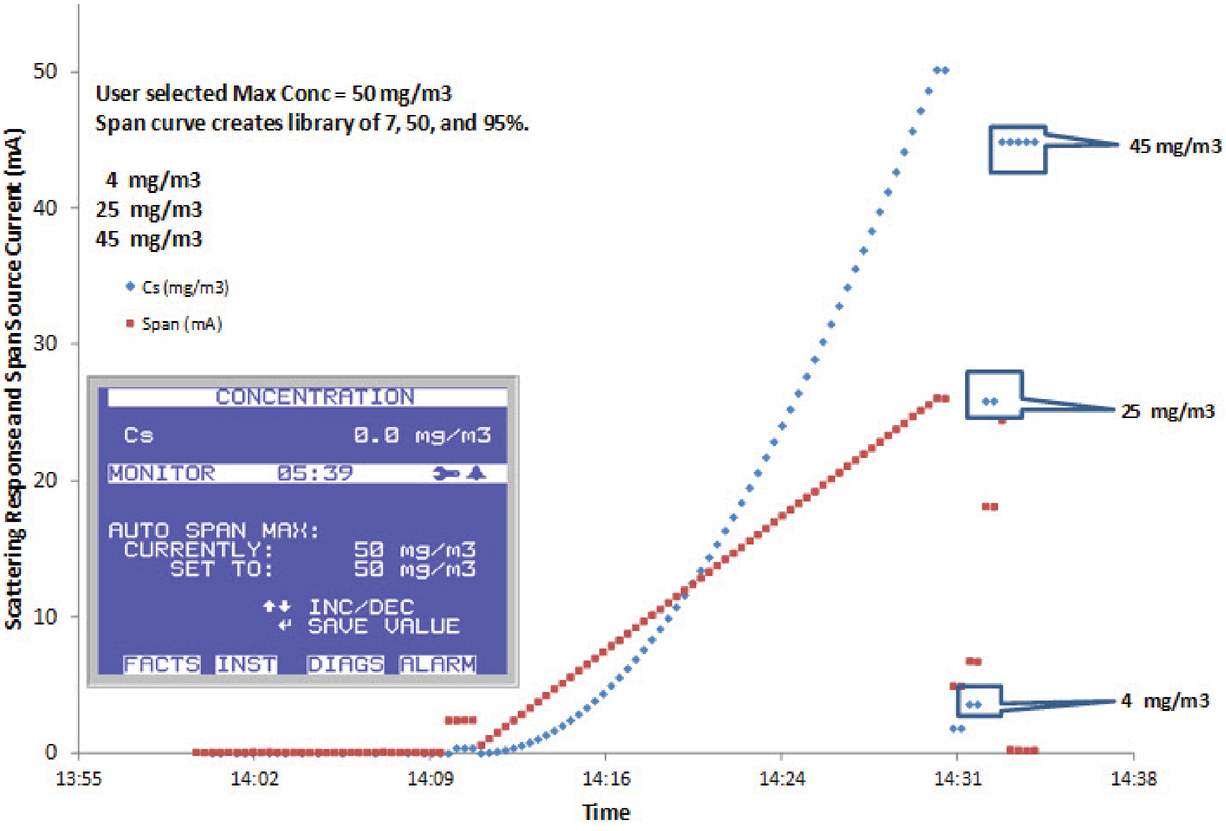


Figure 7: Thermo Scientific PM CEMS collocated precision response. 1 min. concentration July 2013- CFPP Wet FGD.



CONCENTRATION
Cs 0.0 mg/m3
MONITOR 05:39
AUTO SPAN MAX:
CURRENTLY: 50 mg/m3
SET TO: 50 mg/m3
↑↓ INC/DEC
↵ SAVE VALUE

Figure 8: Auto span curve supports daily single point and quarterly multi-point checks.

Figure 7 demonstrates superb collocated precision over a lengthy comparison study.

Figure 8 demonstrates the daily zero span checks generated by increasing the span source current (mA). The quarterly audits may be generated without the need to remove the system from operation. Using the automated curve generation and multi-set points, a quarterly audit can be done remotely and without significant down-time.

Conclusion

Beta testing of the Thermo Scientific PM CEMS has been completed and full production has begun. Field results show an accurate and reliable instrument that can accommodate any changes in wet FGD plant parameters or conditions that affect particulate characteristics. Continued testing at multiple locations, including at cement kilns and industrial boiler stacks, will further verify the instrument's performance.

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

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