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Real Time Measurement Of Particulate At Low Concentration From The Emission Of Stationary Source In The Steel And Power Industries Using a TEOM™ based Emissions Monitor

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Abstract

Historically, measurements of particulate matter emissions from large stationary sources to comply with regulatory standards have employed a variety of methods depending on local agency requirements. More recently, with the establishment of regulatory norms for member states of the European Union, new methods have been established to provide a common basis for evaluating emission sources. In the USA, measurement of PM in emissions sources must be performed in accordance with U.S. EPA Method 5 or, in some cases, Method 17. As with the historical methods used in Europe and the USA, one of the newer methods, EN 13284-1 is based on filtration of particulate matter from a sample collected in-situ and isokinetically and requires the filter to be analyzed in a laboratory. The repeatability of a measurement made with any of the manual methods can be influenced adversely by factors including handling and transport of the filter, conditioning the filter before and after the sampling, and filter weighing. Also, because the measurement using the manual methods can only represent the average emission over the time period sampled, some important data like transitory concentration, stratification in the duct being sampled and the influence of the variation in parameters such as velocity, temperature and pressure on the particulate concentration is difficult or impossible to determine. Consequently, these limitations prompted customers of Rupprecht and Patashnick Company to request the company to develop a new method based on its patented Tapered Element Oscillating Microbalance (TEOM™) technology.

While this new method, named the TEOM Series 7000 Source Particulate Monitor, provides an in-situ measurement collected by filtering source gases at isokinetic sampling conditions, the filter handling and weighing processes are completely different. A filter is placed on the top of the hollow-tube, oscillating element that is housed in a temperature controlled mass transducer assembly. As a carefully controlled vacuum is applied to the opposite end of the tapered element, source gases are extracted from the stack isokinetically and passed through the filter thereby capturing any particulate matter that was entrained in the sample gases. As the filter weight increases with the accumulation of particulate matter, the frequency of oscillation decreases. The change in frequency can be determined in real-time and converted to mass. Tracking mass change with collected sample volume over time permits calculation of mass concentration measurements that can be continuously reported and/or reported as an average over a user specified time period. The

method also incorporates procedures to dry the sample filter prior to and after the test in-situ and to recover any residual particulate matter left in the sample inlet during sampling thereby eliminating measurement errors introduced by filter handling, transport, etc. The ability of the Series 7000 method to measure and report data in real-time, can increase the amount of information available for characterization of process or control system variability or for calibration/correlation of indirect source measurement techniques such as triboelectric, optical or beta attenuation.

Since it is important to understand the agreement between the different methods, and characterize the performance of the new, TEOM-based method this paper reports on a series of tests comparing the TEOM Series 7000 method to NF EN 13284-1 (for low concentration emissions), and NFX 44052 (for high concentration emissions). Results of the twelve test runs performed at the steel mill indicate that the Series 7000 provides a valid measurement equivalent to the reference methods and confirms the conclusion of other laboratories like the TÜV Rheinland who evaluated the Series 7000 in 2001. The evaluation also allowed evaluation of the Series 7000 for calibrating or auditing indirect automatic measuring systems for PM. Results of the tests also found that the Series 7000 method is well suited for the calibration of continuous measuring system using light scattering, transmissionometry or beta attenuation methods. The evaluation also showed that the monitor was robust and well adapted to the industrial environment while being easy to use and reliable.

In a second series of tests, conducted at a large, coal-fired power plant located in the mid-western U.S., paired TEOM Series 7000's were used to evaluate the systems' capacity to make precise, real-time measurements with very short measurement time response. This precision evaluation was conducted in conjunction with assessment of stratification of a PM emissions source with respect to PM at the stack's normal sampling locations. This series of tests found excellent agreement between in the paired Series 7000 trains and showed how the Series 7000 method can be used to rapidly provide detailed information regarding stratification in a sampling plane. Results indicate that the sampling location would be suitable for installation of a PM AMS.

Keywords: particulate matter, source sampling, stack sampling, real-time isokinetic PM measurement

Introduction

As reported in a paper presented at CEM 2002 [Burgher, 2002], Rupprecht & Patashnick Co., Inc. developed a new instrumental method for measuring the particulate matter concentration in emission sources. This method, named the TEOM[®] Series 7000 Source Particulate Monitor (“TEOM SPM”), incorporates R&P’s patented TEOM technology and significantly enhances the amount of particulate matter emissions information that can be achieved from conducting an emissions testing program. For instance, when siting particulate matter continuous automatic measuring systems (“PM AMS”) it is important that the monitor is installed such that it will collect a representative sample regardless of the emission unit operating load. Secondly, as currently available PM AMS do not directly measure particulate matter mass, it is necessary to establish and verify the PM CEMS monitor accuracy over a range of operating conditions using methods such as EN-13284-1, EPA Method 5, ISO 9096 or the TEOM Series 7000.

While TEOM SPM method provides an in-situ measurement collected by filtering source gases at isokinetic sampling conditions, as does recognized reference methods, the filter handling and weighing processes are completely different. With a TEOM SPM, a filter is placed on the top of the hollow-tube, oscillating element that is housed in a temperature controlled mass transducer assembly. The mass transducer is affixed to the end of a long sample probe that allows the mass transducer to be positioned in an emission source. By applying a carefully controlled vacuum to the opposite end of the tapered element, source gases are extracted from the stack isokinetically and passed through the sample filter. The filter captures any particulate matter present in the sample gas stream. As particulate matter accumulates, the filter weight increases which results in decreasing the tapered element oscillating frequency. The change in frequency can be determined in real-time and converted to mass. The result is mass concentration measurements that can be continuously reported and/or reported as an average over a user specified time period. Sample filter conditioning prior to and after the test can also be accomplished in-situ thereby eliminating measurement errors introduced by filter handling, transport, etc. The ability of the Series 7000 method to measure and report data in real-time, can increase the amount of information available for characterization of process or control system variability or for calibration/correlation of indirect source measurement techniques such as triboelectric, optical or beta attenuation.

Since it is important to understand the agreement between the different methods used to make source PM emissions measurements, this paper reports on a series of tests designed to evaluate the performance of the Series 7000 method in comparison to NF EN 13284-1 (for low concentration emissions) and NFX 44052 (for high concentration emissions). In the first set of tests conducted by the laboratory LECES with the support of Ecomesure, the TEOM SPM method was compared to NF EN 13284-1 and to NFX 44052 in three different sources at a steel mill. Following the methods comparison tests, the Series 7000 was then used to calibrate an opacity-based continuous emissions monitor.

It is also important that the reference method used to calibrate or audit an automatic measuring system for PM be inherently precise regardless of source conditions or test operators, etc. For example, while European standards such as EN 14181 and U.S. standards such as Performance Specification 11 (PS-11) do not explicitly include precision requirements for reference method measurements, the correlation of the automatic measurement system to the reference method can be significantly influenced by the precision of the reference method measurements. To demonstrate the precision of the TEOM Series 7000 method when used in real-world test

conditions, a second series of tests, conducted in the fall of 2003, were devised testing to evaluate the precision of method in an emission source produced by a coal-fired, power plant. This series of test were also designed to investigate particulate matter emissions stratification at two sampling locations normally used for emissions permit limit compliance determinations.

Background - Series 7000 Measurement Theory, Configuration and Operation

The Series 7000 allows sample collection inside a stack or duct through a filter while automatically maintaining isokinetic sampling conditions. The filter is affixed to one end of the mass transducer thereby allowing the collected particles to be weighed continuously resulting in a real-time measurement of the particle mass concentration. The TEOM mass transducer uses a short, straight inlet nozzle tube to isokinetically sample the flue gas transporting it just a few millimeters to the filter. The mass transducer is a hollow tube, clamped on one end and free to vibrate at the other. An exchangeable filter cartridge is place over the tip of the free end. This "tapered element" vibrates precisely at its natural resonant frequency. A precise electronic counter measures the frequency that has a direct relationship with mass. The relationship, expressed below, between mass and frequency can be derived from the simple harmonic oscillator equation [Patashnick, et.al, 1991].

$$f^2 = K_0 / m \quad (1)$$

where, f = frequency of oscillation

K_0 = calibration constant

m = mass

The calibration constant of the tapered element can be established by measuring the frequency of the tapered element with a filter of known mass installed and without a filter. Applying the relationship described by equation 1, the value of K_0 can be calculated as shown below:

$$K_0 = (m_2 - m_1) / (1/f_2^2 - 1/f_1^2) \quad (2)$$

The tapered element system is constructed using non-fatiguing inert material and since K_0 is a function of the (non-changing) physical characteristics of the tapered element system, the tapered element retains its calibration indefinitely. Once K_0 has been determined for a particular tapered element, it can be used for mass measurements.

If the element is oscillating at the frequency of f_a and has a frequency response of f_b after an unknown mass is collected on the filter ($\Delta m'$), $\Delta m'$ can be obtained as a function of f_a , f_b and K_0 using the following equation:

$$\Delta m' = K_0(1/f_b^2 - 1/f_a^2) \quad (3)$$

Tracking frequency with time provides the mass rate. When the mass rate is combined with the sample flow rate through the filter, mass concentration of the sampled gases can be directly calculated and in real-time. During normal operation, the temperature of the mass transducer is maintained a few degrees above the stack temperature to provide the frequency stability necessary for measurement of very small mass changes with high temporal resolution. To automatically control isokinetic sampling rates, the system incorporates measurement of source gas velocity, temperature and gas density / molecular weight. Velocity is measured with a "S" type Pitot tube assembly while the gas temperature is measured with a "K" type thermocouple. The gas density / molecular weight determination is provided by

measuring carbon dioxide with a non-dispersive, infrared monitor, oxygen with a paramagnetic monitor and moisture using a differential flow technique patented by R&P. All of these parameters are measured in real-time and input into the system's onboard computer to automatically perform the necessary calculations for computing isokinetic sampling rates. This information is then used to set and control the sampling rate using a measurement-control feedback loop.

Case Study 1: R&P TEOM Series 7000 Evaluation in Steel Mill Source Emissions

The major objectives of this study were:

1. Compare R&P TEOM Series 7000 to the European and French Manual Standard Method (FR EN 13284).
2. Evaluate TEOM 7000 real-time data output, ease of use for conducting emissions tests, and investigate capability for generating complete results on-site.
3. Evaluate TEOM 7000 as a method to calibrate an opacimeter as a PM mass emissions monitor.

A series of twelve test runs in three different sources at a steel mill were conducted by the laboratory LECES with the support of Ecomesure to compare the TEOM SPM method to NF EN 13284-1 and to NFX 44052. All tests were performed under normal operating conditions of each emission unit. One TEOM SPM and one (1) manual reference method sampling train were operated such that simultaneous, co-located samples were collected. The TEOM SPM was operated in the continuous mode following the method instructions that are integrated into the system's computerized operating system. All Series 7000 test measurements and analyses were performed on-site. The manual method trains were operated in accordance with the NF EN13284-1 procedures. Results of the tests are shown below.

Table 1 - Agglomeration Plant Test Results

Test Run	Dust Concentration (mg/m ³)		Relative Difference (%)
	Automatic Method (TEOM SPM)	Manual Method (NF EN 13284-1)	
1	79.9	85.5	-6.5
2	123.1	115	7.0
3	88.4	101	-12.5
4	74.4	83.3	-10.7
Test Average	91.5	96.2	-4.9
Test Conditions:	Ave. stack temperature: 80°C Stack diameter: 2 m Ave. stack gas velocity 9 m/s		

Table 2 – Coke Oven Test Results

Test Run	Dust Concentration (mg/m ³)		Relative Difference (%)
	Automatic Method (TEOM SPM)	Manual Method (NF EN 13284-1)	
5	3.0	3.5	-14.3
6	4.0	4.6	-13.0
Test Average	3.5	4.1	-13.6
Test Conditions:	Condition 5: Stack temperature: 35°C Stack diameter: 2 m Gas velocity: 18 m/s		

Condition 6:	Ave. stack temperature:	184°C
	Stack diameter:	4 m
	Ave. stack gas velocity:	5.3 m/s

Table 3 - Electric Arc Furnace Test Results

Test Run	Dust concentration (mg/m ³)		Relative Difference (%)
	Automatic Method (R&P 7000)	Manual Method (EN 13284-1)	
7	6.8	6.0	13.3
8	56.2	56.9	-1.2
9	5.4	5.0	8.0
10	0.9	0.7	28.6
11	2.1	1.8	16.7
12	2.2	2.0	10.0
Test Average	12.3	12.1	1.7
Test Conditions:	Ave. stack temperature:	115°C	
	Stack diameter:	2.5 m	
	Ave. stack gas velocity:	11 m/s	

In a second set of tests conducted at the steel mill on an agglomeration unit, the TEOM SPM was used to calibrate two Oldham EP1000 Opacimeters. The Series 7000 was installed so that the sample extraction points were near the laser path area of the EP1000. The number of TEOM SPM sampling points on the sampling traverse axis was determined per the procedures specified in EN 13284-1. The duration of each TEOM SPM sample point was approximately five (5) minutes per point. Following the completion of each sample traverse line, the EP 1000 was adjusted to agree with the traverse average reported by the TEOM SPM. This process was repeated until the EP 1000 and R&P 7000 agreed. Result of each calibration test run are shown in the following tables.

Table 4 - Agglomerator Stack 1

Time	R&P 7000 (mg/m ³)	Oldham EP 1000 (mg/m ³)	Temperature (°C)	Humidity (%)
8:29 to 9:41	42	81	124	4.7
10:05 to 11:12	31	61	121	8.8
13:40 to 14:38	58	45	123	4.7
15:22 to 16:24	53	34	127	5.5
10:33 to 10:48	37	46	121	6.6
11:28 to 11:41	28	40	114	10.1
13:44 to 14:13	43	45	116	6.5

Table 5 - Agglomerator Stack 2

Time	R&P 7000 (mg/m ³)	Oldham EP 1000 (mg/m ³)	Temperature (°C)	Humidity (%)
9:25 to 9:51	11	4	50	4.4
10:21 to 10:36	14	21	51	4.6
10:48 to 11:09	10	17	50	4.7

11:22 to 11:45	14	14	51	2.2
11:56 to 12:45	10	11	52	6.1

Case Study 2 : Comparison of TEOM SPM to EPA Method 5 and Stratification Analysis

To illustrate the use of the TEOM SPM for conducting stratification studies to support siting of particulate matter automatic measurement systems (PM AMS), one set of paired train test runs was performed to investigate the degree of stratification in the sampling lines normally used for compliance testing. Prior to the stratification test runs, a set of paired train tests were conducted with the monitor's sample probes positioned at fixed locations near the center area of the stack for the purposes of evaluate the precision of the monitors used for stratification testing. Testing was conducted at a utility plant in the Mid-western U.S. that primarily uses a subbituminous coal from the Powder River Basin (PRB) in the State of Wyoming. During testing, the plant was operating at normal base load conditions.

For the stratification tests, both TEOM SPM systems were operated in the traverse mode following the method instructions that are integrated into the system's computerized operating system. Stack gas velocity and temperature, sample gas molecular weight and gas density measurements used for calculation and setting of isokinetic sampling rates were determined using the TEOM SPM onboard measurement systems. For the precision test, both TEOM SPM systems were operated in the continuous mode. Stack gas velocity and temperature and sample gas density and molecular weight determinations were also made using the onboard measuring systems. All Series 7000 test measurements and analyses were performed on-site.

First, to investigate the precision of the co-located TEOM SPM systems, two identically configured TEOM SPM systems were installed in adjacent sampling ports. The sample probes were inserted so that the probe nozzles were located at the centermost point of the stack as described in EPA Method 1. After each system's sample filter was desiccated to a stable mass, sample collection was started and test measurements were taken for approximately 1.5 hours. Care was taken to start and end the test period for each monitor simultaneously to minimize the potential for temporal changes in the PM emission rate to influence the precision analysis.

For the second test investigating PM stratification, the monitors were installed and configured to measure PM concentrations at three discrete locations along the sample traverse lines for each test port. The probes for each monitor were installed in the same ports that were used for the co-location test. Sample measurements were taken for about 20 minutes at each traverse point for a total test time of approximately one hour. As with the precision test, each monitor was programmed to start and end sampling at the same time.

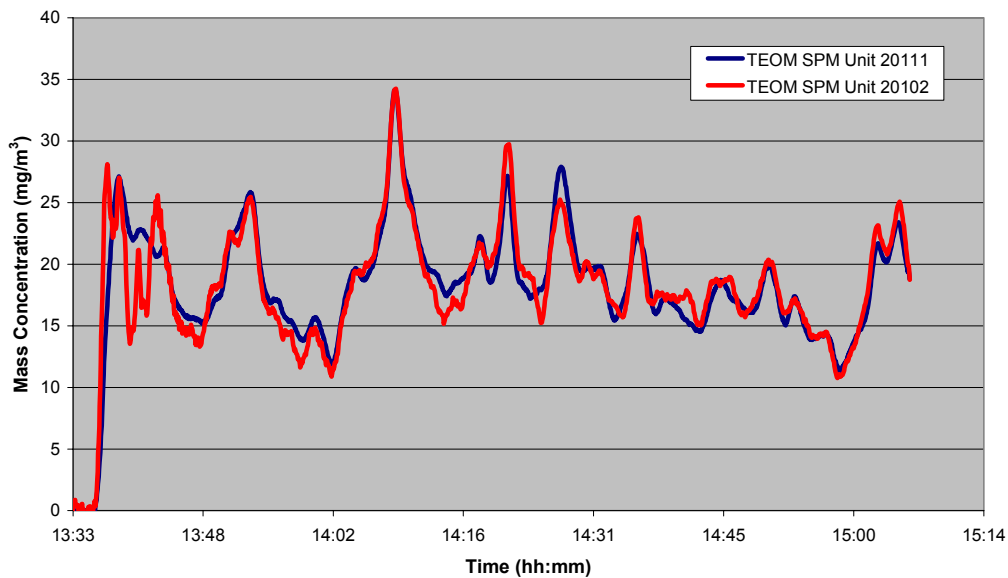
Results from the co-located precision (co-located) test indicate that the difference between the two monitors, when located within the centroid area of the stack, is less than 8%, on average. Results for the traverse test found close agreement between the monitors at all points including the third traverse points were the same points used for the precision test. Since the two monitors showed good agreement during the fixed sample location test, and again at all three traverse point locations, it can be concluded that stratification of particulate matter is not present, at least in the areas tested. Results are summarized below in Table 6 and Figures 1 and 2. The charts shown in Figures 1 and 2 are constructed using the two-minute rolling average mass

concentration for each system clearly demonstrating the precision of the method even for very short term measurements.

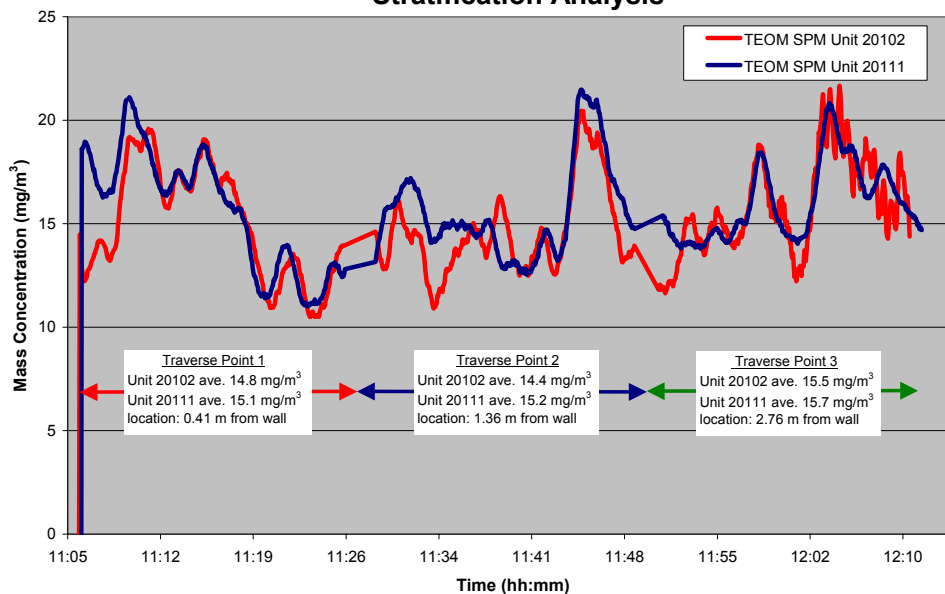
**Table 6 - TEOM SPM – Stratification Analysis
Coal-fired Power Plant – Midwestern U.S.**

Test Type	Traverse Point	Distance from Wall (m)	TEOM SPM Unit 20102 conc. (mg/m ³)	TEOM SPM Unit 20111 conc. (mg/m ³)	Rel. % Diff.
Co-located		2.76	21.1	19.6	7.7%
Traverse	1	0.41	14.83	15.10	-1.8%
"	2	1.36	14.38	15.22	-5.7%
"	3	2.76	15.46	15.70	-1.5%
"	Traverse Test Averages		17.54	16.77	4.5%
Test Conditions:					
Co-located Test:		Ave. stack temperature:	160.0°C		
		Stack diameter:	9.3 m		
		Ave. stack gas velocity:	19.7 m/s		
Traverse Test:		Ave. stack temperature:	152.8°C		
		Stack diameter:	9.3 m		
		Ave. stack gas velocity:	19.0 m/s		

**Figure 1 - Fixed Sampling Location (Co-located) Test
Coal-fired Power Plant Emission Source (Midwest U.S.)
Precision Analysis**



**Figure 2 - Traverse Test
Coal-fired Power Plant Emission Source (Midwest U.S.)
Stratification Analysis**



Conclusions

The evaluation found that the Series 7000 method is well suited for the calibration of continuous measuring systems using light scattering, transmission or beta attenuation methods. The evaluation also showed that the monitor was robust and well adapted to the industrial environment while being easy to use and reliable.

Results of the test runs performed at the steel mill indicate that the Series 7000 provides a valid measurement equivalent to the reference methods and confirms the conclusion of other laboratories like the TÜV Rheinland who evaluated the Series 7000 in 2001. The evaluation also showed that the monitor was robust and well adapted to the industrial environment while being easy to use and reliable.

Results of the testing conducted in the coal-fired power plant emission source showed excellent agreement between co-located Series 7000 monitors while also showing the sampling locations to be essentially non-stratified with respect to particulate matter. Furthermore, testing using the Series 7000 found that stratification analysis could be conducted very rapidly with high reliability thereby, minimizing impacts on plant operations while potentially reducing the overall costs of conducting these types of test programs.

References

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