Proceedings of 9th Diesel Engine Emission Reductions Conference
Newport, RI, August 24-28th 2003

TRANSIENT, REAL-TIME, PARTICULATE EMISSION MEASUREMENTS IN DIESEL ENGINES

Sreenath Gupta, Jonathan Shih, Greg Hillman and Raj sekar
Argonne National Laboratory

Russel R. Graze
Caterpillar

Shirish Shimpi and William T. Martin
Cummins, Inc.

Del Pier
Sierra Instruments, Inc.

ABSTRACT

This paper reports our efforts to develop an instrument, TG-1, to measure particulate emissions from diesel engines in real-time. TG-1 while based on laser-induced incandescence allows measurements at 10 Hz on typical engine exhausts. Using such an instrument, measurements were performed in the exhaust of a 1.7L Mercedes Benz engine coupled to a low-inertia dynamometer. Comparative measurements performed under engine steady state conditions showed the instrument to agree within ±12% of measurements performed with an SMPS. Moreover, the instrument had far better time response and time resolution than a TEOM® 1105. Also, TG-1 appears to surpass the shortcomings of the TEOM instrument, i.e., of yielding negative values under certain engine conditions and, being sensitive to external vibration.

NOMENCLATURE

M	Mass at the end of oscillating element (mg)
K_o	Constant
f	Frequency (Hz)
MC	Mass concentration (mg/m^3)
T	Time (s)
LII	Laser Induced Incandescence
σ	Standard deviation

INTRODUCTION

Continued stringent emission regulations over the last decade have lowered the allowable particulate emission levels over an order of magnitude. As a result the particulate emission levels from current engines are so low that their measurement becomes a challenge. Quite often particulate emissions are at a level comparable with the minimum detection levels of presently available instruments. With anticipated future regulations to become more strict, particulate-measuring instrumentation with minimum detection levels ≤ 0.1 (mg/m^3) are required.

Per EPA guidelines, presently the particulate emissions from heavy-duty trucks are regulated based on the mass collected on filter papers over a prescribed transient cycle [1] in addition to that over specific engine steady-state conditions. In certain regions of the transient cycle, especially during rapid accelerations and heavy load conditions, the engine combustion occurs under fuel rich conditions leading to heavy particulate formation. A particulate measurement instrument with real-time capability could well serve to identify such regions of high particulate emission levels in order to devise strategies for particulate emission mitigation over the cycle. Addressing such a need, a number of research groups have been evaluating various technologies to measure particulate emissions in real-time. Recently, Moosmuller et al. [2] evaluated five different instruments for real-time particulate measurement. Based on such a study and the recent study performed at Ford motor company [3], the Tapered Element Oscillating Microbalance, TEOM®, appears promising.

Alternately, an emerging technology for real-time particulate measurement is laser-induced incandescence. This technology remains attractive as it has minimum detection levels of the order 0.001 (mg/m^3) and allows real-time measurements up to 50 Hz. Further still, it can be combined with laser Rayleigh scattering to potentially measure aggregate particle size and number density. In this paper we report the performance of an instrument based on such a technique with that of the most recent version of tapered element oscillating microbalance, i.e., TEOM® 1105. The principles behind both the instruments are presented first. Subsequently, the performance of these instruments during steady state and transient operation of a passenger car diesel engine are presented.

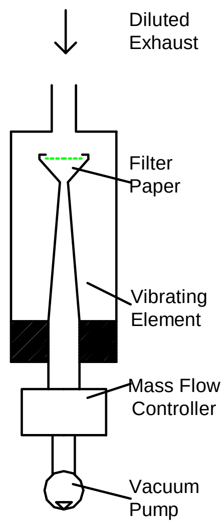


Figure 1. Schematic of a TEOM®

TAPERED ELEMENT OSCILLATING MICROBALANCE

Tapered Element Oscillating Microbalance (TEOM) is an instrument marketed by Ruprecht and Patashnick Company, NY. A brief discussion of the technology behind this instrument is given below.

TEOM® consists of a small filter paper suspended at the end of an elastic element (*cf.* Fig. 1). A diluted stream of exhaust is drawn through the filter by using a vacuum pump at the base of the element. As particles get deposited on the filter paper the natural frequency of vibration of the element changes. The mass at the end of the oscillating element is calculated as

$$M = \frac{k_o}{f^2}, \quad (1)$$

where, k_o is a constant specific to the oscillating element and f the measured natural frequency of vibration. Mass concentration, MC, is determined by drawing the aerosol sample at a constant flow rate and is given by

$$MC = \frac{1}{V}\frac{dM}{dt} = \frac{1}{V}\frac{-2k_o}{f^3}\left(\frac{df}{dt}\right) \quad (2)$$

where, V is the sample volume flow rate. As noted above, accurate mass concentration measurement entails measurement of f as well as df/dt with sufficient accuracy.

As documented in references 4-6, the performance of TEOM has been improved over the years. However, the following issues remain in its use:

1) During engine operating conditions with excessive humidity in the exhaust, the filter paper absorbs water vapor. This results in artifacts during transient measurements, such as, negative measurements during rapid decelerations. Ron Jarrett and coworkers [7] recently developed a correlation to reduce such errors during transient measurements. Additionally, removing water vapor in the sample by using Naphion membranes is currently being evaluated by the manufacturer of TEOM®.

2) The TEOM® instrument is sensitive to vibration levels typical of engine test-cells and its physical location requires careful attention.

LASER INDUCED INCANDESCENCE

Laser induced incandescence (LII) entails the heating of particulates using a high-power laser pulse. Following the laser pulse, the ensuing gray body radiation when collected in a narrow band of wavelength yields information of local volume fraction. While details of this technique and variants of it can be garnered through references 8-10, the basic configuration followed in this study is a given in Fig. 2. The 532 nm output from a pulsed Nd:YAG laser is shaped into a vertical sheet using a combination of cylindrical lenses so that the focal plane lies at the center of a quartz sample cell. A fast response photocell placed downstream of the sample cell monitors the laser power to the required pulse energies. The LII signal was detected by a PMT detector placed at right angle to the in coming laser beam at 430±5 nm. The peaks of the LII signal were measured using a high-speed data acquisition card.

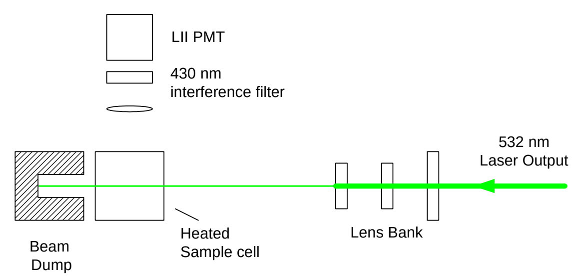
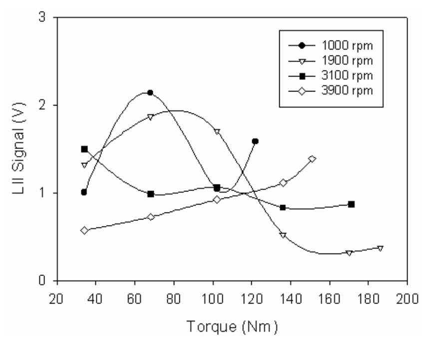


Figure. 2 Schematic of LII experimental setup.

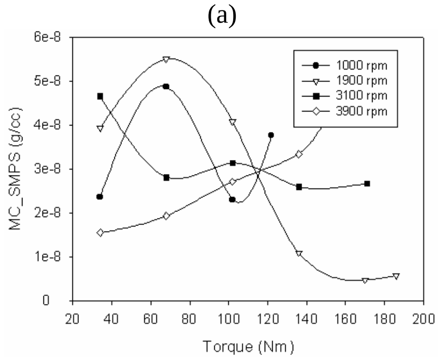
Diesel exhaust aerosol diluted with prefiltered air is passed through the sample cell at the rate of 3 – 6 SLPM. The walls of the sample cell were maintained at a temperature slightly higher than the aerosol to avoid particle deposition due to thermophoresis.

The above arrangement was contained in an enclosure roughly 24” x 15” x 8” and could be placed in an engine test-cell (*cf.* Fig. 3). For the remainder of this paper this prototype instrument will be referred to as TG-1.

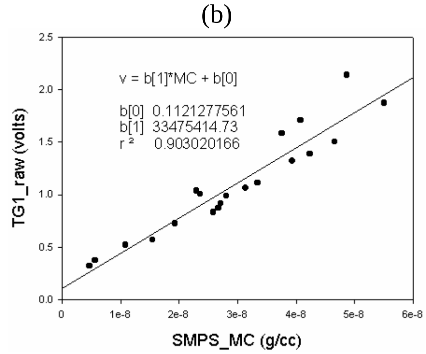
Figure. 3 Panoramic view of prototype TG-1 instrument.



(a)



(b)



(c)

Figure. 4. Signal comparison of TG-1 with SMPS.

PERFORMANCE EVALUATION

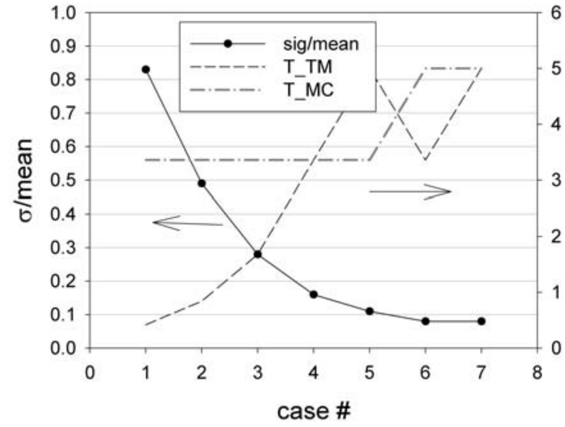
Measurements were performed with TG-1 on the exhaust aerosols of a Mercedes-Benz 1.7 L engine coupled to a low-inertia dynamometer. These are discussed below.

ACCURACY

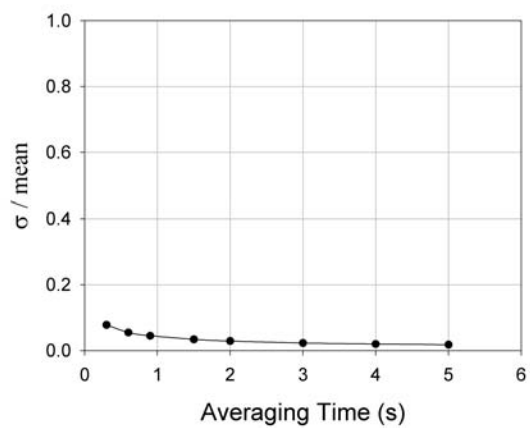
A SMPS instrument from TSI, Inc. was used for signal calibration. Such calibrations were performed by operating the engine under several steady-state conditions spanning over the entire engine map. The particle size distributions given by the SMPS were used to obtain the local particulate mass concentrations. A particle density of 1.7625 (g/cc), which is the same as soot density, was assumed in such calculations. As seen in Fig. 4, the particulate mass concentrations varied over one order of magnitude and the LII signals varied ±20% when compared to SMPS measurements and ±12% full scale. However, it is not clear whether such variations are attributable to the instrument or to the engine itself. However, such calibrations were used for subsequent measurements.

TIME RESOLUTION

From eqns. 1 and 2, it is seen that the mass concentration measurement accuracy in a TEOM® is determined by the accuracy in determining both f as well as df/dt. For transient measurements the accuracy in measuring df/dt governs the accuracy. Several measurements were performed by operating the engine under various steady state conditions. The two time constants T_TM and T_MC in the TEOM software were varied and measurements were performed (*cf*. fig 5a). Such measurements indicate that a minimum of 5-second moving average is required to obtain reliable measurements. On the other hand, in TG-1 the sampling frequency is governed by the laser repetition rate (10 Hz typical) and the measured LII signal is directly proportional to MC. As a result TG-1 requires just 0.3 second moving average, i.e., 3 point moving average, for comparable performance (*cf*. fig. 4b). This translates to TG-1 having 17 times better time resolution under the present configuration. If desired the time resolution can be enhanced to 0.06 sec by using a 50 Hz laser.



(a)

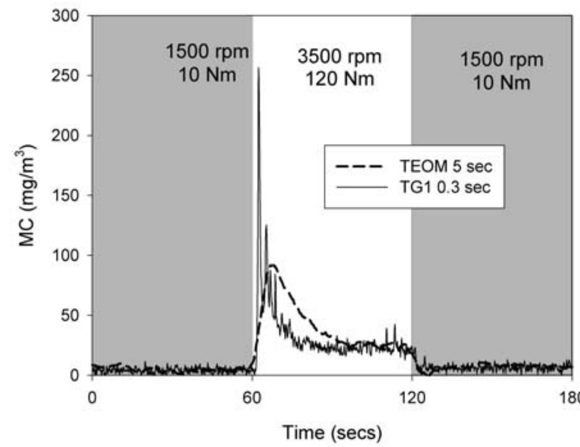


(b)

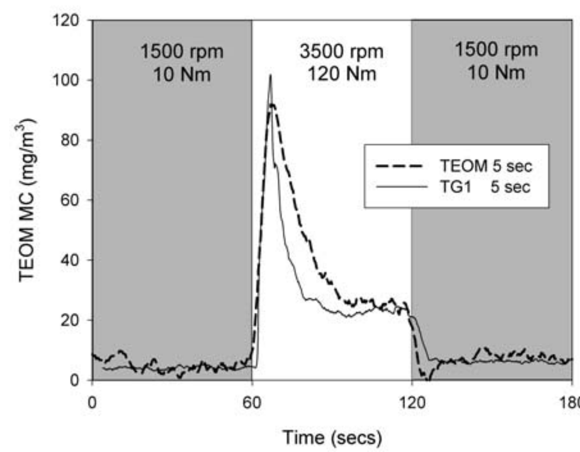
Figure. 5 (Standard deviation/mean) signal for (a) TEOM 1105 and (b) TG1. Mean value = 8.03 x 10^{-8} (g/cc).

The instrument response to step changes in engine modes is shown in Figs. 6a and 6b. As seen in Fig. 6a, the lower time resolution of TEOM results in under measuring of particulate emission spikes. However, as evident from Fig. 6b, both instruments' responses averaged using a 6 second moving average closely agree with each other. Though not significant, one notices that during the second step change TEOM® still suffers from water vapor desorption resulting in slightly negative values. Whereas, such response is not seen in measurements performed using TG-1.

It ought to be recognized that overall time response of either instrument depends upon the time delay introduced by sample transfer lines, sample flow rate and other factors based on measurement configuration. These could not be exactly quantified in this set of measurements with sufficient accuracy for a direct comparison. However, from Fig. 6a one gathers TG-1 to have better time response.



(a)



(b)

Figure. 6. TEOM 1105 and TG1 measurements for mode changes in engine operation. (a) at best performance of each instrument (b) each instrument set to 5 sec moving average.

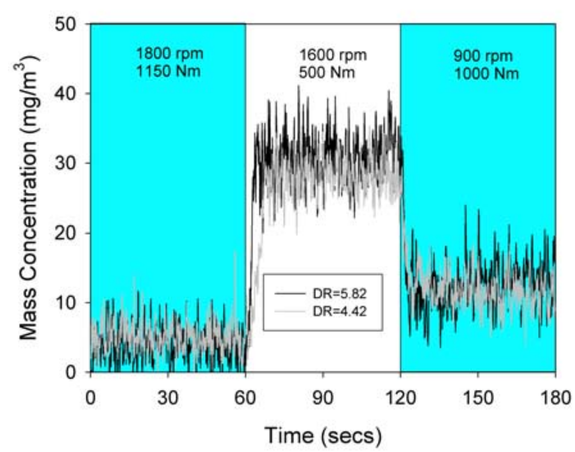


Figure. 7. Agreement between measurements performed on two separate days shows excellent repeatability of TG-1.

REPEATABILITY

Measurements performed on the exhaust of a Caterpillar C10 engine on two separate days are shown in figure 7. As evident the repeatability of TG-1 is excellent and does not appear to depend on the dilution ratio used.

TRANSIENT MEASUREMENTS

The main advantage of TG-1 is its ability to measure in real-time. The current prototype uses a 10Hz laser and consequently samples particulate mass concentration at 10 Hz. Typical measurements over a part of the urban driving cycle are shown in fig. 8. As evident there is appreciable agreement between both of these instruments.

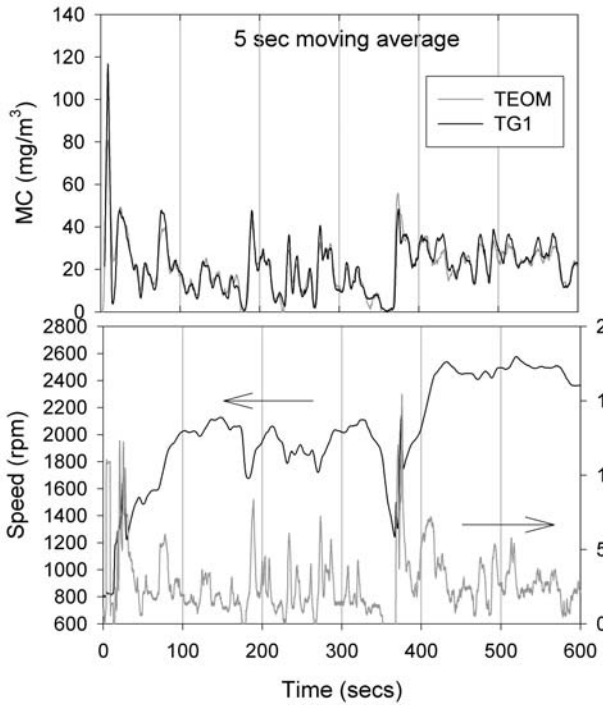


Figure. 8 TG1 and TEOM 1105 measurements during engine operation simulating a typical driving cycle.

CONCLUSIONS

An instrument based on laser-induced incandescence was developed for real-time measurement of particulate emissions from diesel engines. This instrument, called TG-1, was evaluated against commercially available instruments for accuracy, time resolution, time response, repeatability and overall performance. The most notable conclusions are mentioned below.

1) Measurements performed under various engine steady state conditions show TG-1 signals to vary ±20% compared to those measured using an SMPS instrument. The overall variation i.e. of ±12% full scale is typical of particulate measurements.

2) Step changes in engine operation were used to identify the instrument time response. Tg-1 appears to have 0.1 sec time response whereas the value of TEOM® 1105 could not be determined in this effort.

3) However, the step change operation showed TG-1 to have 0.3 sec time resolution, which was 16.7 times lower than that of a typical TEOM® 1105.

4) Furthermore, the measurements performed on two separate days agreed closely exhibiting the excellent repeatability of the TG-1 instrument.

5) Also, unlike TEOM, the TG-1 instrument, due to the nature of its principle of operation, is insensitive to water vapor in the exhaust sample and test-cell vibration levels.

In spite of the above success, concerns remain in the adaptation of LII for routine PM measurements in engine test-cells. Most importantly, it is debatable whether LII measures total PM or just elemental carbon. Conflicting arguments are provided in the literature. Future tests are warranted investigating this issue.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support from US DOE–OFCVT with Gurpreet Singh as the contract manager.

REFERENCES

1. Code of Federal Regulations: Protection of Environment, Office of Federal Register National Archives and Records; US government printing office: Washington DC, 1996; 40 CFR 86.1, subpart N.
2. Moosmuller, H., Arnott, W. P., Rogers, C. F., Bowen, J. L., Gillis, J., and Pierson, W. R., "Evaluation of five instruments for the real-time measurement of diesel particulate emissions," 10th CRC On-road Vehicle Emissions Workshop, San Diego, CA, March 27-29, 2003.
3. Podsiadlik, D. H., Chase, R. E., Lewis, D. and Spears, M., "Phase-based TEOM measurements compared with traditional filters with diesel PM," SAE 2003-01-0783.
4. Whitby, R., Gibbs, R., Johnson, R, Hill, B., Shimpi, S., and Jorgenson, R., "Real-time diesel particulate measurement using a TEOM," SAE820463.
5. Whitby, R., Johnson, R., and Gibbs, R., "Second generation TEOM filters – diesel particulate mass comparisons between TEOM and conventional filtration techniques," SAE 850403.
6. Okrent, D. A., "Optimization of a third generation TEOM monitor for measuring diesel particulate in real-time," SAE 980409.
7. Jarrett, R. P., and Clark, N. N., "Evaluation of methods for determining continuous particulate matter from transient testing of heavy-duty diesel engines," SAE 2001-01-3575.
8. Gupta, S. B., Poola, R., and Sekar, R. R., "Issues for measuring diesel exhaust particulates using laser-induced incandescence," SAE 2001-01-0217.

9. Sommer, R., Schraml, S., and Liepertz, A., “Application of the LI^2SA-Soot-Sensor for the characterization of modern low emission engines” 6th International ETH-Conference on Nanoparticle Measurement.

10. Snelling, D. R., Smallwood, G. J., Sawchuk, R. A., Neil, W. S., Gareau, D., Chippior, W., Liu, F., Gulder, O., and Bachalo, W. “Particulate matter measurements in a diesel engine exhaust by laser-Induced incandescenec and standard gravimetric procedure” SAE 1999-01-3653.