

Sensing of Particulate Matter for On-Board Diagnosis of Particulate Filters

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ABSTRACT

New particulate sensing technologies are currently being readied for production to meet the on-board diagnostic (OBD) regulations associated with diagnosing diesel particulate filter (DPF) efficiency. The threshold levels for diagnosis have been tightened starting in 2013, requiring a new approach beyond the current techniques which often rely on differential pressure sensing across the filter. A new sensor has been developed to directly detect the particles passing through the DPF and estimate the cumulative particle flow. Using this information, an estimate can be made of the filter's efficiency and an associated diagnosis of its ability to meet emissions requirements. In this paper we will discuss the sensor's operating principle, accuracy and repeatability. Experimentally-observed variability of exhaust particulate matter will be compared to simulated deposition of soot¹ in a modeling environment.

¹The authors acknowledge that "soot" is an imprecise colloquial term relating to chimney deposits. Soot is used for brevity in this paper and is intended to be interchangeable, unless otherwise noted, with "particulate matter," since the sensor in discussion has the potential to collect the full range of particulate matter in the exhaust, as opposed to only a purely carbonaceous fraction [4].

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INTRODUCTION

The diesel particulate filter has become an essential part of the aftertreatment system for diesel engines. As with other emissions control components, the diagnosis of the DPF is required in order to insure that it is performing its intended filtering function at a high enough level of performance to meet requirements. The regulatory requirements for DPF diagnosis are changing, with the diagnosis threshold in the United States being reduced from emissions five times higher than the regulatory limit to 1.75 times the regulatory limit, as shown in Figure 1 below [1,2,3].

The filtering capability of a DPF can be compromised by axial or radial cracks caused by excessively high temperatures in the DPF or high thermal gradients. These types of situations can arise, for example, in the case of an uncontrolled DPF regeneration in conditions where exhaust oxygen content is high, exhaust flow rate is low, and soot loading in the DPF is high [5].

Today's DPF diagnosis is typically done using feedback from a differential pressure sensor which gives a reading proportional to the pressure drop across the DPF. While this approach is acceptable for the current diagnosis thresholds, it

appears that it will not be sufficient to meet the newer tighter regulations. For example, during an oral presentation at the 2010 SAE On-Board Diagnostics Symposium [6], Isuzu presented results of a study which concluded that a differential pressure diagnostic cannot detect all failure modes and a differential pressure method is not likely to be suitable for meeting the stricter regulations.

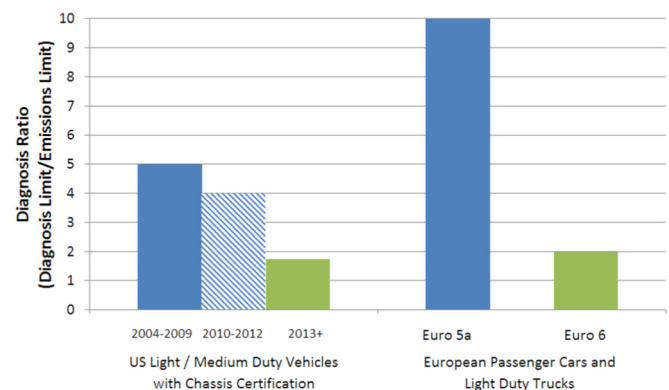


Figure 1. DPF Diagnosis Regulatory Requirements

The new regulations have less separation between a limit-good DPF and a limit-bad DPF. A limit-good DPF would permit particulate emissions on the test cycle equaling just slightly lower than one times the regulatory emissions threshold, or “1X”. A limit-bad DPF would permit particulate emissions on the test cycle equaling just slightly higher than the diagnosis threshold, for example, “2X”. A difficult challenge in diagnostic systems is showing sufficient discrimination between “good” and “bad” components once the statistical variation of the diagnostic technique is taken into account. A numerical way to quantify this discrimination is through the calculation of a value called DMSS, which stands for Difference of the Means divided by the Sum of the Standard deviations. DMSS is calculated as the difference of the means of two distributions, divided by the summation of the standard deviations of both distributions (“good” and “bad” in this case). An example of two distributions is shown below in [Figure 2](#), with the populations having means of 1 and 2, respectively, to represent “1X” and “2X” populations. Each population varies by $\pm 40\%$ at 3 standard deviations. It can be seen that the red “2X” distribution is wider, since 40% variation around a mean of 2 is larger in absolute terms than 40% variation around a mean of 1. The overlap in these two distributions, which is approximately at 1.4, is the area where risk of misidentification of events belonging to the two different groups can occur. The goal of a diagnostic system is to minimize this area of overlap such that the diagnosis is correct. This can be quantified by setting a target DMSS value of 3, for example, which corresponds to less than 0.15 % of the tails of each distribution overlapping past a threshold set at three standard deviations from the mean of each distribution.

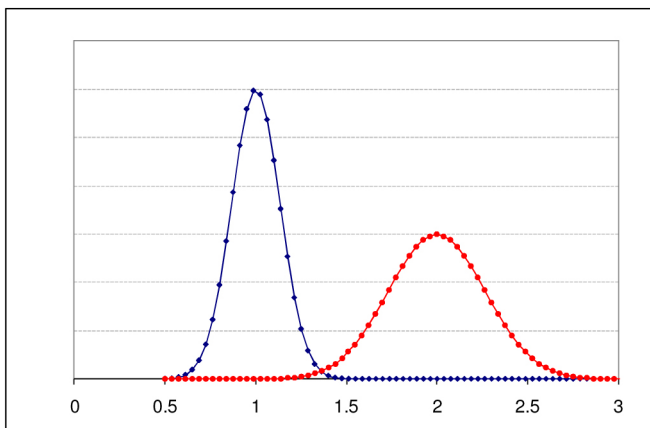


Figure 2. Statistical Distributions of 2 Populations

The use of a particulate matter (PM) sensor to directly sense the particulates in the exhaust stream is a new approach which holds the potential to increase the accuracy of DPF diagnosis such that the new OBD regulations can be met with acceptable DMSS levels. The PM sensor can be inserted in the exhaust stream after the DPF as shown in the diagram in [Figure 3](#) below. In this position, the particulates that come

through the filter can be measured by the sensor. The packaging under the vehicle can dictate where a PM sensor is best located, and since the DPF can be located before or after the selective catalytic reduction (SCR) catalyst, a PM sensor must be designed for robustness to urea exposure.

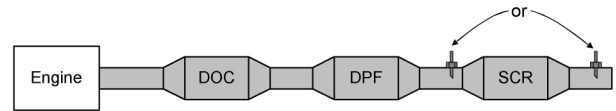


Figure 3. Exhaust System with PM Sensor

PARTICULATE MATTER SENSOR REQUIREMENTS

The particulate matter sensor is located in a very harsh environment - both internal and external to the exhaust pipe. [Table 1](#) below captures a summary of the main PM sensor requirements.

Table 1. Summary of PM Sensor Requirements

Wide Operating Temperature Range
Rugged and Robust to Exhaust Exposure
Quick Time to Sensor Ready
Accurate
Features to Support Diagnostic Requirements
Provision for Regeneration (Heater)
Wide Exhaust Velocity Range
Senses near Center of Exhaust Pipe
Robust to Water Condensate Exposure

Externally, the sensor must be able to withstand complete submersion in water without allowing any moisture into the housing. The wire harness must withstand exposure to radiant heat transfer from the hot exhaust system nearby. Further, the vehicle underbody environment can expose the sensor to gravel bombardment which is capable of transferring significant impact energy to the sensor body.

Internal to the exhaust pipe, a PM sensor located behind a DPF is exposed to water impingement from condensed water released by the DPF back face. During a DPF regeneration, exhaust temperatures at the DPF outlet can reach temperatures in the 650 to 700° C range. If the DPF is overloaded or the regeneration becomes uncontrolled, the temperatures can climb even higher. Short durations of over-temperature as high as 950°C are possible for a runaway situation. It is important that the sensor continues working after such an occurrence to diagnose a failed DPF, since the source of many DPF failures is high temperature gradient exposure by the DPF substrate. However, being located behind the DPF does offer poison and ash exposure advantages, since the DPF tends to filter them along with the particulate matter. Exhaust gas can also contain sulfates which can form corrosive acids, and if positioned behind a

urea SCR catalyst, the sensor will be exposed to ammonia and urea.

The particulate matter sensor technology presented in this paper requires the sensor element to be above the dew point temperature in order to differentiate between conductive water particles and engine particulates. Since the DPF has a large thermal mass, it can take several minutes for the exhaust gas outlet temperature to rise above the dew point. During this time the sensor signal is depressed and not usable for detecting engine particulates. The farther back the PM sensor is located, the longer the delay for the dew point temperature to be reached. Thus, it is advantageous to be as close as possible to the DPF for achieving quicker time-to-operation. Since the test cycle for evaluation of a DPF failure has limited time, the sooner the PM sensor is above dew point, the more time is available verification of DPF failure before setting a failure code.

Unlike gas constituents, which tend to quickly diffuse in the exhaust, particulate matter is solid matter suspended in air that does not diffuse quickly. Thus, care must be taken in locating the sensor so that objects do not mask the particulate matter from the sensor. This is important both upstream and downstream of the sensor so that the gas velocity vectors are not affected.

Since the sensor must receive solid particles onto the surface of its internal element, conventional contaminant protection coatings that require a torturous path to reach the element sensing surface are not feasible. Therefore, the PM sensor must rely in part on the DPF to prevent the contaminants from reaching the surface of the element. These contaminants typically consist of Calcium, Zinc, Phosphorous, and Sulfur primarily coming from the engine oil, but to some extent also from the fuel. Large amounts of acid can be produced in a diesel exhaust system, especially behind a DPF and SCR system. Since the PM sensor is not normally heated, this acid can reside on the internal sensor components for a significant amount of time. Further, the acid can enhance the oxidation of the iron found in the exhaust components with the oxidized material having the potential to find its way onto the sensing electrode. Iron oxide is a semiconductor which can become conductive in the measuring temperature range of the sensor.

Since the PM sensor must be a fairly open design to flow particulate matter across the electrode face, it can be challenging to regenerate the sensor to a temperature that insures a complete oxidation of the particulate matter under the full range of temperature and flows. This is especially true for post DPF diesel locations which tend to run below 300°C and have relatively high velocities. In vehicles with 12 volt electrical systems, the amount of available power to heat the sensor is limited.

PM SENSOR DESIGN AND OPERATION

The PM sensor, shown in Figure 4 with its internal element, is composed of a lower shield to guide exhaust flow to the element, the sensing element, a sensor body to allow the sensor to be mounted to the exhaust pipe, and an upper assembly which makes the electrical connection from the sensing element to an external wiring harness. The sensor element consists of a non-conductive alumina-based ceramic substrate with a sensor electrode pattern made from conductive precious metal in order to withstand the temperature of the application. The sensing element of the sensor is shown larger in Figure 5 with its important features labeled. The sensing element includes a bias resistor and an integrated heater near the sensing electrodes.

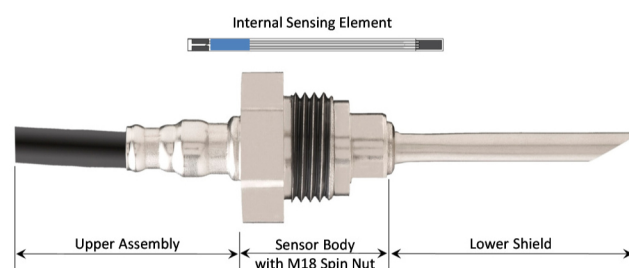


Figure 4. Particulate Matter (PM) Sensor



Figure 5. Particulate Matter (PM) Sensor Sensing Element (Enlarged)

Figure 6 shows a comparison between the exhaust insertion depth of typical switching oxygen sensor and the PM sensor. As shown, the PM sensor is designed to be inserted towards the centerline of the exhaust pipe. Since it is unknown where a failure could occur in a DPF, the PM sensor may be mounted on the opposite side (radially) of the failure. By locating the entry opening of the PM sensor near the centerline of the exhaust pipe, the sensor has a higher probability to detect soot from any radial direction sooner than if the inlet hole were located towards one side of the pipe. This enables the PM sensor to be mounted closer to the DPF outlet than a shorter sensor. A traditional estimate of 10 pipe diameters for the flow to become mixed [7] on a 75 mm diameter exhaust pipe would require 525 to 750 mm of mixing distance and for a 125 mm diameter exhaust pipe the distance would be 875 to 1250 mm. This is often difficult to package in an exhaust system and might locate the sensor in such a distant position that it takes an excessively long time

to reach temperatures above dew point where the sensor can be reliably used.

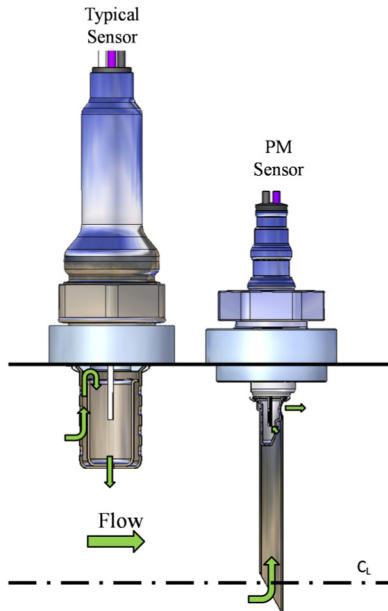


Figure 6. Sensors in Exhaust Flow with Pipe Centerline Shown

Figure 7, shows 3-D CFD modeling results in a cross section of the PM sensor with exhaust flow boundary conditions of 15 m/s velocity and 200°C temperature. As shown, the design of the sensor is oriented so that the inlet to the outer shield faces the oncoming exhaust allowing a high dynamic pressure to feed exhaust to the sensor electrode. This orientation is accomplished via alignment features in the sensor and the mounting boss in the exhaust pipe. The sensing electrode is also oriented to the incoming exhaust to minimize the part to part variation from various entry points. The design of the sensor lower shield allows a large amount of exhaust sampling and thus fast response to soot particles that are in the exhaust.

In the absence of soot, there is very low electrical conductivity between the electrodes. As soot accumulates on the surface of the sensor between the electrodes, the soot particles begin to overlap to bridge the gap. Because the soot particles are electrically conductive, the conductivity between the electrodes increases and is measured as part of an electrical circuit.

An equivalent circuit of the sensor and detection circuit is shown in Figure 8. R_{pm} , the particulate matter resistance measured by the sensor electrodes, decreases as soot accumulates. R_{bias} is a fixed resistance allows diagnosis by maintaining a fixed resistance when there is no particulate matter on the sensor. The alumina substrate has a finite resistance of $R_{substrate}$. These three resistances are configured in parallel, with the smallest resistance dominating the sensor's output resistance at any given time.

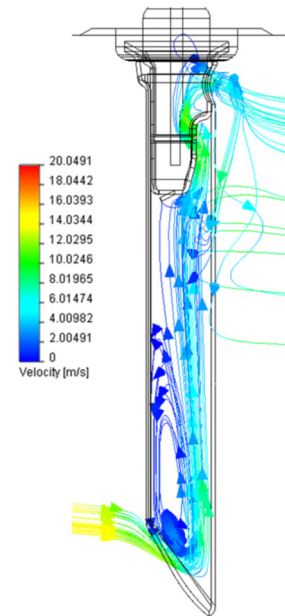


Figure 7. Result of CFD Modeling at 15 Meters per Second Exhaust Velocity

In order to minimize system cost, the sensor operates without the need to generate high voltage for operation. Both the sensing element and the sensor heater operate at or below the normal 14 volts found in a vehicle electrical system. The simple electronics interface needed to read the sensor can be located in the engine control module or in a dedicated sensor control unit. The sensor's heater is powered during the Regeneration Time described below using a standard exhaust sensor heater control circuit with current feedback.

SENSOR OPERATION

The sensor's operation consists of two parts: (1) collection and detection of particulate matter in the Sensing Time, and (2) "regeneration," in which the collected material is oxidized at high temperature and thus removed from the sensing portion of the sensor's element, in the Regeneration Time. Using a reference voltage of 5 volts with a circuit like the one shown in Figure 8, the resulting voltage waveform from the sensor and circuit in engine exhaust conditions is shown in Figure 9. Each repetition of the waveform is called a "cycle," with the cycle being composed of a Sensing Time and a Regeneration Time, as depicted in Figure 10.