

A New Miniaturized Sensor for Ultra-Fast On-Board Soot Concentration Measurements

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ABSTRACT

In this article we present a design of a new miniaturized sensor with the capacity to measure exhaust particle concentrations on board vehicles and engines. The sensor is characterized by ultra-fast response time, high sensitivity, and a wide dynamic range. In addition, the physical dimensions of the sensor enable its placement along the exhaust line. The concentration response and temporal performance of a prototype sensor are discussed and characterized with aerosol laboratory test measurements. The sensor performance was also tested with actual engine exhaust in both chassis and engine dynamometer measurements. These measurements demonstrate that the sensor has the potential to meet and even exceed any requirements around the world in terms of on-board diagnostic (OBD) sensitivity and frequency of monitoring. Further to potential OBD applications, this has the capacity to be used as an engine and combustion diagnostics sensor, for example to detect misfiring, cylinder combustion variability, exhaust gas recirculation flowrate, etc.

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INTRODUCTION

Meeting stringent particulate matter (PM) and particle number (PN) emission limits for diesel light-duty and heavy-duty vehicles necessitates the use of a diesel particle filter (DPF) in the exhaust line. As a consequence, on board monitoring of the DPF performance is required first to make sure that the DPF operates correctly and, second, to confirm that emission limits are not violated under real-world operation. The latter is performed by on-board diagnostic (OBD) sensors which make sure that specific OBD threshold limits (OTL) are not exceeded.

Currently three different operation principles are implemented in commercial DPF performance monitoring sensors. The first technique relies on particle deposition and resistance measurement [1, 2]. The particles are deposited onto a collection surface, where electrodes are separated by an electrically insulating material. The deposited conductive particles gradually change the surface conductivity. By

measuring the resistance between the electrodes it is possible to assess the amount of soot deposited to the surface, which is then linked to the soot concentration in the exhaust line. In principle, this method is based on an integral measurement of particle concentration over a period of time, and requires periodic regeneration of the deposition surface for a new deposition cycle to begin. The frequency of those regenerations is a measure of particle concentration. Therefore, the response time of these sensors is from several seconds to minutes, depending on the particle concentration.

The second family of sensors comprises those measuring the amount of deposited soot into the DPF filter. This can be estimated by either measuring the pressure difference over the filter or by measuring microwave transmittance through the DPF [3].

The third measurement technique involves electrical particle detection. For this, the charge of particles following combustion can be utilized, such as in the PMTron sensor [4, 5], where the naturally

charged exhaust particles are collected inside the sensor by an electric field and an amplified electric current proportional to the particle concentration is measured.

The electrical methods described above rely on the conductivity of the emitted particles, hence on particle properties. Therefore, electrical detection methods appear to be in need of engine specific calibration to accurately detect PM or PN OTL exceedances. Moreover, the sensitivity of electrical resistance and DPF soot loading estimation sensors is not enough to enable reduction of current OTL levels, to bring them in line with corresponding emission limits.

On the other hand, many of the widely-used aerosol measurement instruments rely on the diffusion charging of particles by ions generated in a corona discharge. For the measurement of exhaust gas particle concentrations, a simplified electrical instrument based on the diffusion charging was first demonstrated by Ntziachristos et al. [6]. The instrument consisted of a particle charger and a Faraday cup aerosol electrometer. In the years since, that same concept has been used in several rather simple aerosol instruments such as NSAM [7] and DiSCmini [8].

In diffusion charging instruments, the charge acquired by the aerosol during the charging process is not only dependent on the particle number concentration but also on the particle size and this has an effect on the instrument response. However, in typical exhaust aerosol of either diesel or gasoline vehicles, the mean particle size typically remains within a narrow size range. While the particle morphology is known to have a small effect [9], the charging is relatively independent on the particle material [10]. Based on this weak material dependence, this detection method is equally suitable for both conductive soot particles and non-conductive ash particles. However, in order to overcome the morphology effect, the instrument response needs to be determined for exhaust-like aerosol. Diffusion charger based instruments typically offer good correlation and good signal repeatability for a stable size distribution, which also make them a promising approach as an OBD particle sensor.

In this study, a new miniaturized sensor based on particle diffusion charging is presented, with the potential to be used as an OBD sensor or as a general combustion diagnostics sensor. The design of the new sensor is based on the Pegasor PPS-M [11], which have been used for exhaust particle emission measurements [e.g. 12, 13].

OPERATING PRINCIPLE AND SENSOR DESIGN

The operating principle and sensor construction is similar to the Pegasor PPS-M sensor, but in a much more compact form. The unit is now designed so, that the sensor probe, measuring 16 mm in diameter and 40 mm in length, can be positioned directly into the exhaust line. The necessary electronics are integrated to the sensor head, and a CAN serial bus is provided for the data output. Both the sensor probe

and the integrated electronics are placed inside a static shielding to avoid electromagnetic interference. The overall dimensions of the sensor are 190 mm length and 36 mm diameter at the largest point. M18×1.5 thread is provided for the connection to the exhaust line. The sample flow rate of the tested prototype sensor was 3.5 lpm, while the required pressurized air supply was 8 slpm with 1.5 bar overpressure compared to the exhaust line. The current measurement range of the electrometer is ± 2.5 nA.

A schematic of the cross section of the prototype sensor is presented in Figure 1, showing the key components and operational parameters of the design. The operation is based on diffusion charging of the aerosol particles and subsequent charge detection. Like the PPS-M sensor, the new sensor utilizes the escaping current measurement method, where the particles need not be actually collected. The charge detection is realized by measuring the charge that the particles carry away from the electrically floating corona discharge. In order to avoid charger fouling, the corona discharge electrodes are protected by a clean sheath air flow and the ions produced are brought into contact with the sample by a high velocity air stream from the discharge region. The same air stream is used also as a pump flow providing the sample flow for the sensor.

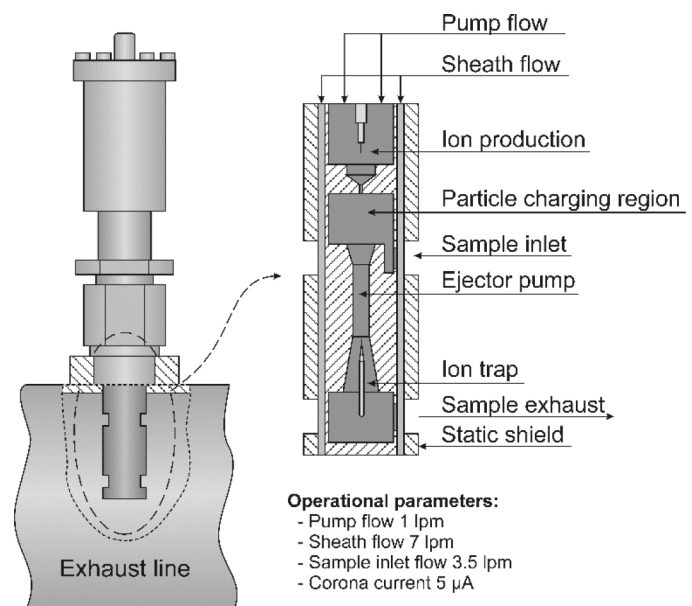


Figure 1. The sensor prototype pictured on the left together with the cross section on the right showing the main components and operational parameters of the sensor design.

Particle charging takes place in the charging region positioned right after the critical orifice separating the discharge region and the sample volume. The sample enters the charging region through the sampling port followed by a sharp bend in the flow channel. The purpose of the bend is to act as a pre-cut impactor preventing the large particles from entering the sensor and clogging the sample flow path. After the charging region the sample flows through the ejector pump. An ion trap is positioned downstream of the ejector pump to remove the excess ions before the sample exits the sensor through the

sample exhaust port. The ion trap is dimensioned so that the cut point is approximately 5 nm, in order to have minimal particle losses. As in the PPS-M sensor design, the sample inlet and exhaust ports are positioned on the same side of the sensor probe to minimize the pressure difference between the inlet and outlet ports. Although the inlet and exhaust ports are relatively close to each other, the sample recirculation is effectively prevented by the high flow velocity of the exhaust flow.

SENSOR RESPONSE AND SENSITIVITY

The sensor output signal is an electrical current produced by the charged particles as they exit the sensor. The sensor response relates this output to the number concentration of the aerosol particles in the sample flow. The operation is based on diffusion charging of the particles, and hence the response is proportional to the charging efficiency. Since the charging efficiency is dependent on particle size, the sensor response is also a function of it. The charging efficiency depends on the $N_t t$ -magnitude, which is the product of the ion number concentration (N_t) and the particle residence time (t) in the charging region. While the charging efficiency could be approximated from the $N_t t$ -product, the ion properties, and the particle size, it is however often approximated to follow a power function of the particle size, shown in equation 1. The parameters a and b in equation 1 are typically determined by calibration, where the charger output signal is compared to the aerosol concentration when using monodisperse aerosol in the laboratory.

$$R_s(d_p) = a d_p^b \quad (1)$$

For the prototype sensor it was not possible to produce monodisperse calibration aerosol in sufficient concentrations for the high volumetric flow rate needed for the calibration. Instead, the sensor output was measured with different polydisperse aerosol size distributions as an input. Then, a fitting routine was used in order to find out the parameter values for the charging efficiency. The response measurement setup is shown in Figure 2. The measured test aerosols were produced by a modified diesel fuel burning heater [14]. The size distribution was controlled by varying the fuel feed and the air flow into the burner. The number-weighted geometric median of the size distribution was varied between 35 nm and 210 nm, while the geometric standard deviation range was 1.6 - 1.8. A scanning mobility particle sizer (SMPS, TSI Inc.), consisting of a model 3071 differential mobility analyzer (DMA, TSI Inc.) and a model 3775 condensation particle counter (CPC, TSI Inc.), was used to measure the size distribution. The total number concentration was measured with a model A20 CPC (Airmodus Oy). In total three ejector dilutors were used for dilution. Two in series, in front of the SMPS, and a third one in series upstream of the CPC. The total dilution ratio for the SMPS measurement was 90:1, and 900:1 for the CPC measurement. Since the particle size distribution was measured after dilution, the measured distributions were monitored not to contain nucleation mode particles.

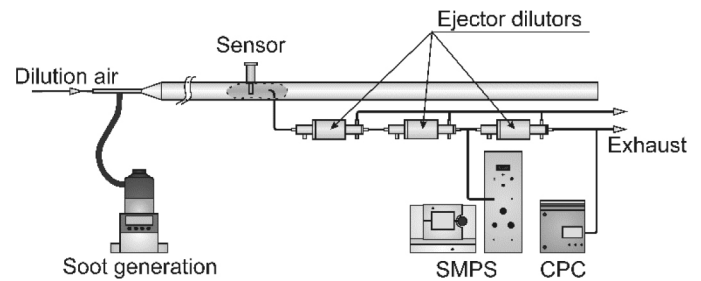
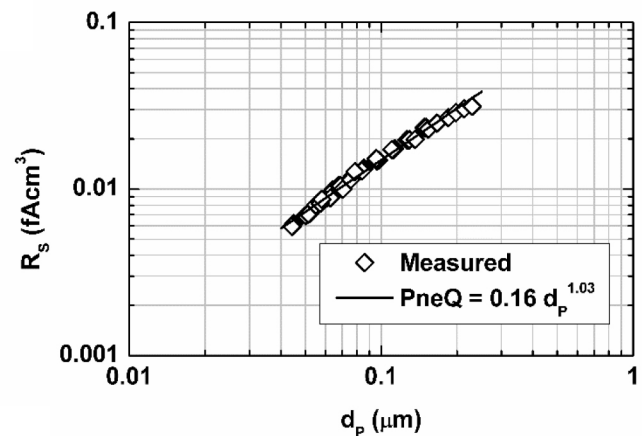


Figure 2. The setup used for the prototype sensor response measurement.

For data processing, the measured total number concentrations were first corrected with the dilution ratio to obtain the total number concentration in the sample line. The measured number size distributions were then normalized to the measured total number concentration of the test aerosol. In order to obtain the values for eq. 1 parameters, the measured sensor signal was compared to a simulated sensor output calculated from the corrected number size distributions using the response function shown in eq. 1. The best fitting values for parameters a and b in the response function were obtained by using a minimum square sum fitting routine. The resulting sensor response is shown in eq. 2 and plotted on Figure 3 together with a correlation plot between the measured and simulated sensor outputs. The measured sensor response points in Figure 3A are plotted as the function of the median diameter of the size distribution weighted with the sensor response.

$$R_s(d_p) = 0.16 d_p^{1.03} \quad (2)$$



A.

Figure 3.