High speed OBD sensor response and time resolution measurements

Antti Rostedt, Ossi Vuorinen, Kauko Janka, Jaakko Yli-Ojanperä
and Jorma Keskinen

Introduction

The unipolar diffusion charging by a corona discharge has been utilized in many real time aerosol measurement instruments. In principle the method is relatively simple: the particles are first charged by the ions produced by the corona discharge and then the charge on the particles is detected with a current measurement. Both the charging process and the electrical current measurement are in theory very fast, which makes a very good starting point for real time measurements. However in practice there are few factors that limit the time resolution of the measurement. For instance the sample residence time inside the instrument sets a clear limitation for the maximum achievable time resolution. Additionally the low signal level in the current measurement sets a limitation to the time resolution. From the current measurement point of view a compromise between the time resolution and the allowed signal noise level must be made.

The particle charging is dependent on the $N_i t$ –product of the charger, which is the product of the mean ion concentration and the particle residence time in the charging region. According to the studies by Davison et al. (1985) a $N_i t$-product value in the order of 10^7 s/cm³ is needed for the particles to reach saturation charge level. Intra and Tippayawong (2011) list several unipolar charger designs and the value for the majority of the chargers, which $N_i t$-product value is reported, falls in this region. The value for ion concentration can be significantly higher. The same overview reports ion concentrations up to 10^{11} 1/cm³. These two values indicate, that the time resolution limit for the charging process can be well below 1 ms.

One major disadvantage of the method is that the output is not only dependent on the particle number concentration, the particle size affects also to the charging process. For this reason the charging properties of the used diffusion charger needs to be known in more detail in order to fully interpret the measurement results. The two main properties affecting to the particle charging are the average number of charges the particles acquire $n(d_P)$ and the particle penetration through the charger $P(d_P)$, both of which are dependent on the particle size d_P. The overall charging efficiency $E_{CH}(d_P)$ is the product of these two terms multiplied by the charge of the elementary charge e and the volumetric flow rate through the charger Q. The charging efficiency of a unipolar diffusion charger is usually approximated to follow a power function shown in equation 1, where the parameters A and B depend on the charger properties and the values for the parameters are obtained with calibration measurements.

$$E_{CH}(d_P) = P(d_P)n(d_P)eQ \approx A{d_P}^B \quad (1)$$

Sensor design

The high speed OBD (HSOBD) sensor utilizes same measurement method as the Pegasor PPS-M sensor but in a much smaller size. In the sensor the ions are produced to a clean air stream, which is mixed with the aerosol sample. The high velocity ion containing air stream is also used as the pump flow in the integrated ejector pump, which provides the sample flow through the sensor. The particles are charged inside the sensor head and the charge taken by the particles is measured without collecting the particles. The measurement method is described in more detail by Rostedt et al. (2014). Apart from the PPS-M

sensor the ion trap collection characteristics cannot be changed in the HSOBD sensor. The sensor is intended for on-board diagnostics (OBD) purposes of vehicles. Picture of the HSOBD sensor and the cross section of the sensor head are shown in figure 1. The sensor is intended to be mounted directly to the exhaust line so that the sensor head is in the exhaust flow.

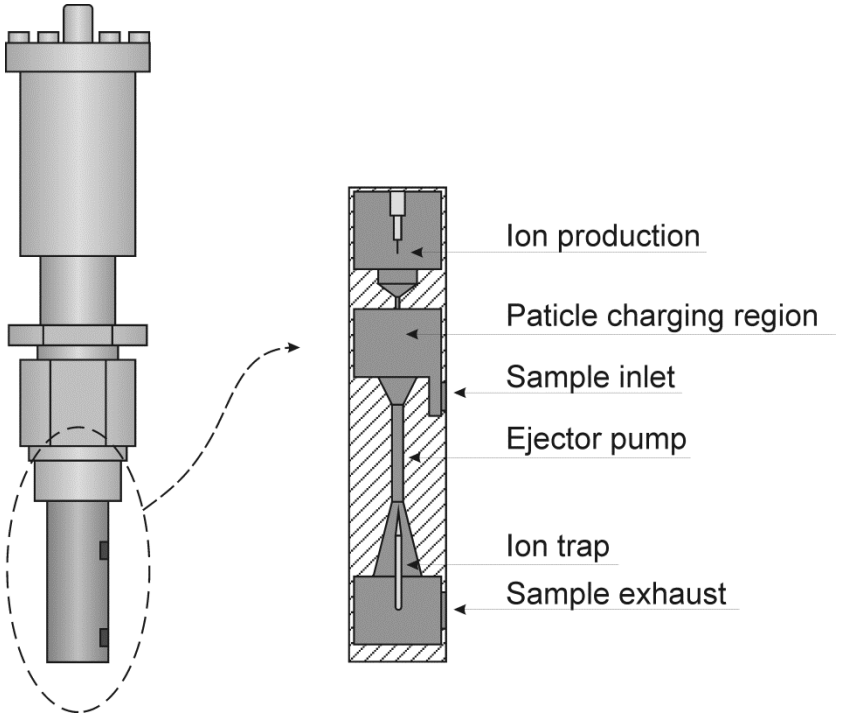

Figure 1. Picture of the HSOBD sensor (left) and a cross section of the sensor head (right).

Sensor response

The HSOBD sensor response equals the to the product of the charging efficiency $E_{CH}(d_P)$ of the charger and the penetration efficiency $P_T(d_P)$ of the ion trap. In practice, because of the highly integrated nature of the sensor mechanics, the effects of these two components cannot be separated. In here the effects of the components are treated as a single charging efficiency (i.e. the ion trap is treated as a part of the charger), but for clarity this charging efficiency is called as the sensor response $R_{HSOBD}(d_P)$. Since the electronics is optimized for speed rather than sensitivity, response measurements with typically low concentration monodisperse calibration aerosols is not possible. For this reason the response was obtained by measuring polydisperse aerosols with varying size distributions and using a fitting procedure to find out the sensor response. The measurement setup used is shown in figure 2. The soot aerosol used in the measurement was generated by a modified heater burning diesel fuel. The generator produces a stable diesel-soot like

test aerosol, which size distribution can be controlled by varying the combustion air feed. During these measurements the median size of the distribution was varied between 34 and 200 nm, while the geometric standard deviation varied between 1.6 and 1.8. The generated size distribution was measured with a Scanning Mobility Particle Sizer (SMPS) consisting of a Model 3071 Differential Mobility Analyser (DMA, Tsi Inc.) and model 3776 Ultrafine Condensation Particle Counter (CPC, Tsi Inc.). A second CPC model A20 (Airmodus Oy) was used to measure the total number concentration of the aerosol. Because of the high concentration needed for the response measurement, a two stage ejector dilutor was used in front of the SMPS and followed by a third ejector dilutor stage before the CPC. The total dilution ratio for the SMPS was 90 and for the CPC 880.

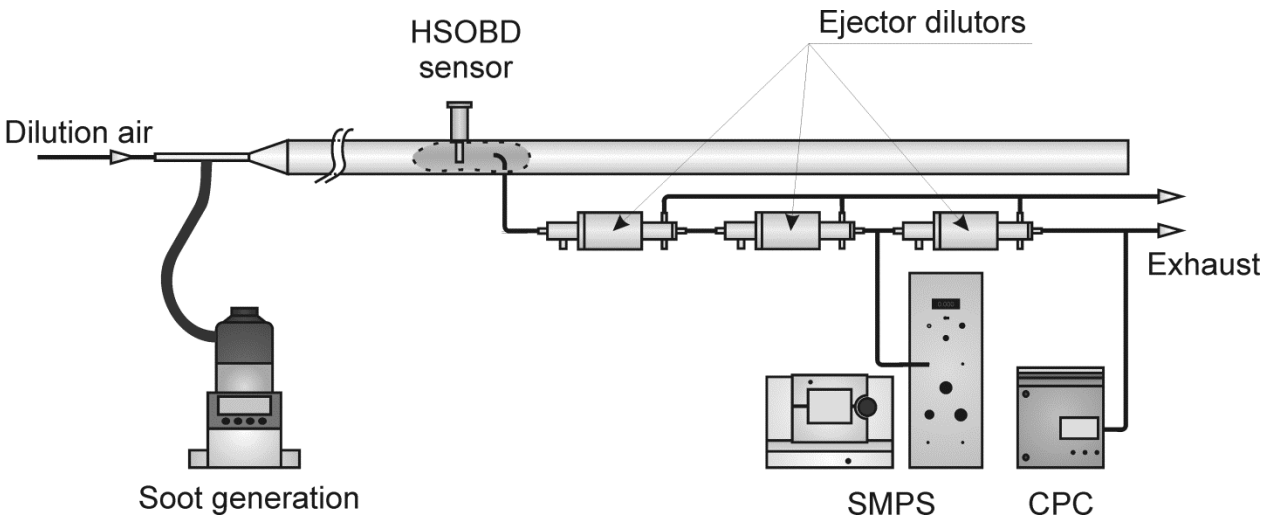

Figure 2. Measurement setup used in the HSOBD sensor response measurement.

In order to find out a fit for the sensor response the sensor output was simulated using the measured size distributions and total number concentrations and a minimization procedure was used to find the best fitting values for the parameters *A* and *B* in equation 1. The parameters fitted to the sensor response are shown in equation 2, where the units used for the response and particle size are facm³ and µm respectively. The resulting sensor response is shown on the left side in figure 3 together with a correlation plot between the measured and simulated sensor outputs on the right. As seen in the figure 3 the response follows the power function fit with a good correlation. The fitted power value of 1.03 is very close to the value 1.05 reported for the PPS-M sensor in Rostedt et al. (2014).

$$R_{HSOBD}(d_P) = 0.16\, {d_P}^{1.03} \quad (2)$$

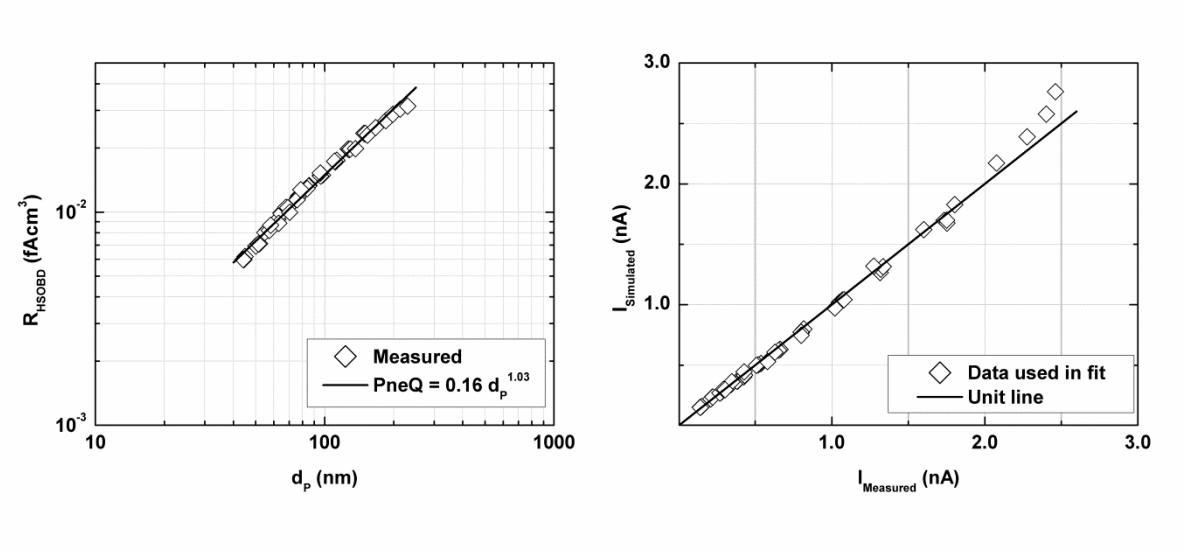

Figure 3. Fitted HSOBD sensor response on the left and correlation between the measured and simulated sensor outputs on the right. The data points on the left plot are measurement results: The sensor output divided with the total number concentration as a function of the median size of the size distribution weighted with the response.

Time response measurement

The HSOBD sensor time response was measured in the same setup as shown above. The only difference was the added small air tube just in front of the sensor inlet. This was used to create a sudden change in the aerosol concentration in the sensor inlet by rapidly blowing a clean air stream towards the inlet of the sensor. The flow rate of the clean air stream was around 70 lpm, while the effective sampling volume of the sensor was approximately 1 cm³. Based on these two values, the time constant for the concentration change was in the order of 1 millisecond. The air stream was switched on and off by using a fast acting magnetic valve. The sudden concentration change was measured with the HSOBD sensor together with the state information of the magnetic valve to help the data alignment. Approximately 100 subsequent repetitions were measured. The repetitions were aligned together and an average signal was calculated. For this average signal shown in figure 4 a step response was fitted (also drawn in figure 4). The best fit for the step response was obtained with a time constant of 18 ms. This gives the HSOBD sensor a value of 40 ms for the 10% - 90% rise time.

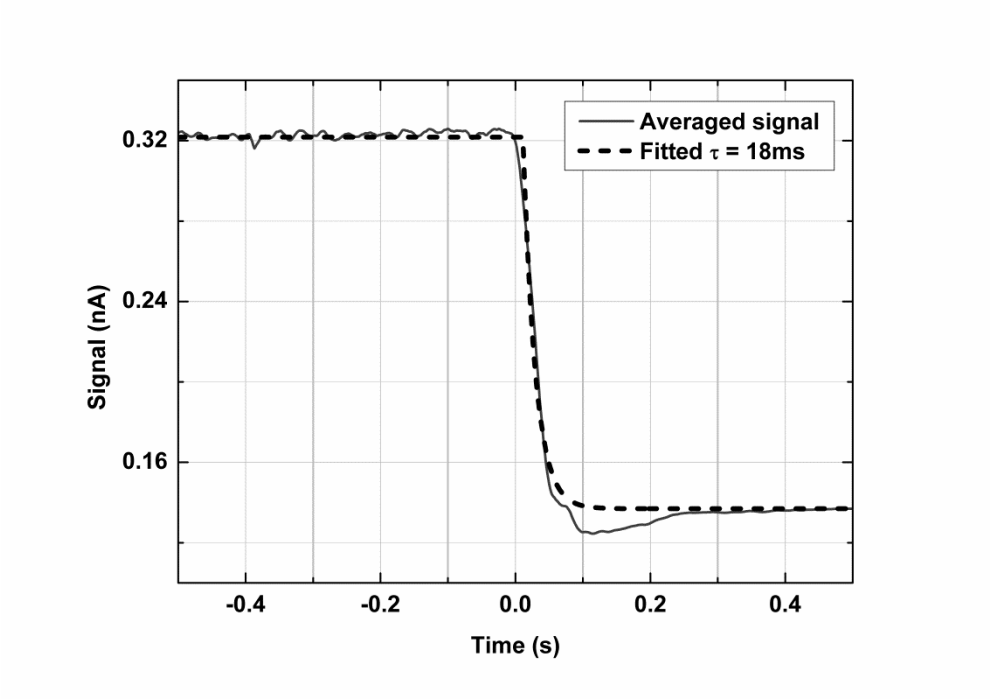

Figure 3. Averaged time response of the HSOBD sensor together with a fitted step response with a time constant value of 0.018 s

Summary

The response of the HSOBD sensor was measured in a test setup with polydisperse soot aerosol. By fitting the simulated response obtained from the measured size distribution and number concentration a sensor response function was found. The response measurements were carried out using size distributions with number median sizes between 34 and 250 nm. The simulated sensor outputs with the fitted response agree very well with the measured outputs. Additionally the time resolution of the sensor was measured by measuring sudden concentration changes produced by air stream controlled by a fast acting magnetic valve. As a result a time constant value of 18 ms was fitted for the step response, which corresponds to 40 ms rise time (10 – 90%).

References

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