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Non-Collecting Electrical Sensor for Particle Concentration Measurement

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ABSTRACT

A novel particle emission sensor based on particle charging and electrical detection is presented. The sensor charges the particles and measures the current carried by the particles exiting the sensor. The measurement is carried out without collecting the particles. Thanks to this principle, the mechanical construction of the sensor can be such that the sensor is not prone to fouling. The intended application of the sensor is the measurement of particle emission of diesel vehicles. The sensor is placed directly in to the exhaust flow of the tested vehicle, and because of that there is no need for any sampling or dilution of the exhaust gas. This together with the electrical measurement method allows rapid time response, and consequently, real time measurement of test cycles or on-road driving.

The sensor was tested in the laboratory and a theoretical model was build to predict the response of the instrument. The model can be used for converting the measured signals to the particle concentration or emission rate. Good correlation with a reference instrument was obtained in a diesel test cycle measurement.

***Keywords*:** Particle; Sensor; Diesel exhaust; Real time.

INTRODUCTION

The need to measure aerosols has increased substantially in recent years–mainly because of the undesirable effects they have on our health and the environment and the role particles play in atmospheric processes and climate change. Particle emissions and ambient and workplace particle concentrations and exposure are measured to ensure that the limits set by the legislation are met and that the public is not exposed to undesirable concentrations of aerosols. The health of the employees needs to be considered, as the number of manufacturing processes where materials pass through an aerosol phase is increasing rapidly, in areas from pigments, powders, and pharmaceuticals to optical fibers. Such applications require constant monitoring at many different locations or portable instrumentation that can be easily transferred between the locations of interest. In addition, with low cost portable instrumentation the particle emission sources could be monitored more easily and more extensively. Although the information obtained with a simple sensor type measurement can be quite limited compared to a full featured measurement set-up, there are some clear advantages. Usually most modern fine particle instruments can provide a lot of detailed information about the aerosol measured, but the cost and complexity of these devices is a major concern. Furthermore when using these devices, there is commonly need for sampling and sample conditioning systems. They not only add on to the cost and complexity, but they can also have some unwanted side effects to the measured sample. Despite its limitations a simple sensor type measurement could be very useful, when monitoring relatively well known aerosol or in particularly when monitoring changes in the aerosol content.

In engine exhaust particle emission measurement, which is the application for the sensor presented in this study, several different measurement techniques have been used. Mohr *et al*. (2005) lists various particle measurement instruments for particle emissions of modern vehicles. Those utilize the most commonly used measurement techniques, including mass based, optical and electrical techniques. A common feature of the listed instruments is that they need sampling and sample conditioning before the actual measurement. Most commonly used sample conditioning includes some kind of a dilution system to dilute and to lower the sample temperature and water content. The use of a dilution system adds delay and averaging to the sample and for comparative results similar dilution system and operational parameters must be used (e.g. Mathis *et al*., 2004). A dilution system also slows the time response of the measurement system. This may be a significant disadvantage when rapid transient phenomena are investigated.

Simple sensor type solutions, such as opacimeter and filter smoke number (FSN), are especially well suited for engine development, inspection and maintenance related particle measurements, where often only relative quantities of the emission are required. The opacimeter (e.g. ISO 3173, SAE J1667), commonly used in inspection tests, measures extinction of light in the exhaust gas in the visible or near infrared wavelength regions and it has been commonly used in the past. The FSN is also widely used as a simple technique to measure diesel particle emission, where the particles are first collected to a filter surface and then the blackening of the filter is measured optically. Although requiring particle collection for the measurement, only simple equipment is needed. A more modern technique capable of on-line soot measurements is laser induced incandescence (LII, Quay *et al*., 1994). The measured soot containing flow is illuminated with a pulsed laser source and the blackbody radiation from the heated soot particles is detected. LII can be used as an imaging measurement, enabling both spatial and temporal measurement of the soot volume fraction and primary particle size of the soot as demonstrated by Will *et al*.

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(1995). The measurement can be used to study the soot formation inside the flame region of a combustion process.

Other promising and relatively simple instruments are the photoacoustic sensor (Petzold and Niessner, 1996) and the diffusion charger (e.g. Ntziachristos *et al.*, 2004). The photoacoustic sensor utilizes the high absorption coefficient of the soot and measures acoustic signals originating from the particles heated by pulsed light source. With the diffusion charger measurement the particles are usually charged using an unipolar corona discharge charger after which the particles are collected with a Faraday cup filter and the charge on the particles is measured as a current signal. The outcome of the diffusion charger measurement is related to the total active surface of the aerosol measured.

In general, electrical measurement methods seem promising, when aiming towards a simple sensor solution for aerosol measurement. The simplicity and ruggedness of the electrical measurement methods are the key properties. Electrical measurement methods also provide fast response times, which make it possible to use them in real time measurements of a changing aerosol. With electrical methods, the particle size or the concentration cannot be measured directly. If the measured aerosol and the properties of the sensor are known, the measured electrical signals can be converted for instance into a number or mass concentration. In emission measurement, the temporal concentration values need to be converted into temporal emission rate values (#/s, mg/s), integrated over time and divided by the produced energy or travelled distance. The current regulations for particle emissions are based on total mass (mg/km, mg/kWh). A proposal for particle number emission measurements (#/km, #/kWh) is included in future Euro V/Euro VI regulations (Regulation (EC) No 692/2008).

In this paper, an aerosol particle sensor capable for measuring particle emission of a diesel vehicle is presented and evaluated (Janka *et al*., 2007; Niemelä *et al*., 2007; Tikkanen *et al*., 2007). The sensor is placed directly in contact with the measured exhaust flow ensuring simple and easy to use measurement set-up. Although the presented sensor is tailored to a focused application, the same principle could easily be used for other purposes as well; in fact a similar measurement method has been previously used in monitoring the air quality in work environments (Lehtimäki, 1983). The sensor presented here is named the Electrical Tail Pipe Sensor (ETaPS) and it is commercially available from Dekati Ltd, Finland.

SENSOR DESIGN

The operation principle of this sensor is based on a non-collective electrical measurement. The system consists of an electrically isolated corona discharge circuit and an electrometer to measure the leakage current from the discharge. In operation, the corona discharge unit, i.e. the probe, is placed inside the flow channel, so that the flow containing particles to be measured flows around and through the probe. A fraction of the particles in the flow pass through the sensor volume where they are charged by the corona discharge. While some of particles may deposit on the sensor's surfaces, the majority exit, and thereby remove charge, from the sensor volume. Because the corona discharge circuit is electrically isolated from the surroundings, this loss of charge can be seen as a leakage current from the system and it is measured by an electrometer. Since we want only the particles to contribute to the measured signal, escaping of ions from the system must be prevented. This is done with the corona electrodes, which also form an ion trap inside the sensor probe. Particles collected inside the probe do not contribute to the measured current; only the charge carried away from the probe with particles will be measured. In this way, the passage of particles through the sensor can be recorded without additional sampling and collection of the particles. The resulting small detection volume located directly in the exhaust stream enables fast response time.

The sensor is placed directly in contact with the measured aerosol flow to simplify the measurement set-up. As a disadvantage this exposes the sensor to a harsh environment where it must tolerate high variations in temperature and flow velocity. The aerosol concentration inside the tailpipe can be really high, of the order of 10^9 1/cm³ at the most. To withstand all this, the sensor must be build so that it is rugged and not prone to fouling. In addition, the electrical measurement method needs good insulators to operate correctly. Insulators need to stay clean and inside the operating temperature range of the insulating materials. For this, the use of cooling and sheath flows must be used. The total sheath air flow rate is 50 L/min, which is less than five percent of the flow rate inside the exhaust line at the most. Based on the tests done, this has negligible effect on the measurement. The designed operation limits of the presented sensor are collected to the Table 1.

The operational concentration range depends on the particle size and flow velocity inside the flow channel. This is due to velocity dependent residence time in charger. The values shown in Table 1 are calculated to cover the whole flow velocity range of 3-50 m/s and particle number median size range of 40-100 nm. For instance for constant flow velocity of 20 m/s, the concentration range is 4×10^3-7×10^8 for a lognormal size distribution with a median size of 100 nm and a GSD of 1.8.

The response time of the sensor is not practically restricted by physical properties of the charging process involved, which makes the method ideal for real time measurement. In the actual sensor the response time is electrically limited to 1 s, but even faster response times could be used if needed. A cross section view of the sensor probe together with an equivalent electrical circuit is presented in Fig. 1.

EXPERIMENTAL SET-UP

The laboratory measurements were made using a measurement setup presented in Fig. 2. The set-up consisted of a channel system, where a ducted fan circulated the air through the tested sensors and an air filter. There were two identical sensor prototypes fitted to the flow channel one after the other. The first sensor (Sensor 1) was primarily used in the tests and the second one (Sensor 2) was used just for comparison. All data presented here is measured with the first sensor. For both sensors the sheath air flow rate was set to 50 L/min. The filter in the set-up cleaned the test flow from particles. An exhaust port was needed, because the feed of the test particles and the sheath flows of the sensors led to an excess flow from the system. During the tests the flow velocity was measured with a flow sensor and it could be varied by the rotation speed of the fan in the range of 1-35 m/s. The channel size, where the sensors were fitted, was 100 mm in diameter and to reduce pressure drop in the system the diameter was 250 mm elsewhere. To ensure stable flow profile around the sensor probes, they were fitted so that there was enough free space in before and after the sensors for the flow to stabilize.

The aerosol sample for the reference measurement was taken from the flow before the sensors and it was diluted with an

Table 1. Designed operation limits of the sensor.

Parameter	Range
Temperature	0-400°C
Flow velocity	3-50 m/s
Particle concentration	10^5-10^8 1/cm³
Sheath air flow rate (total)	50 L/min

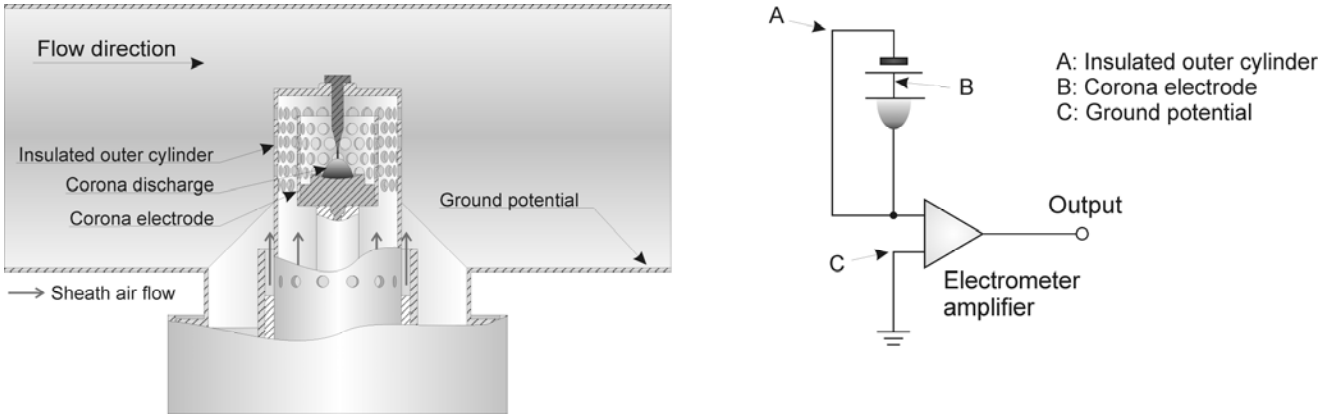

Fig. 1. Cross section view of the ETaPS sensor probe on the left. On the right the equivalent electrical circuit of the sensor.

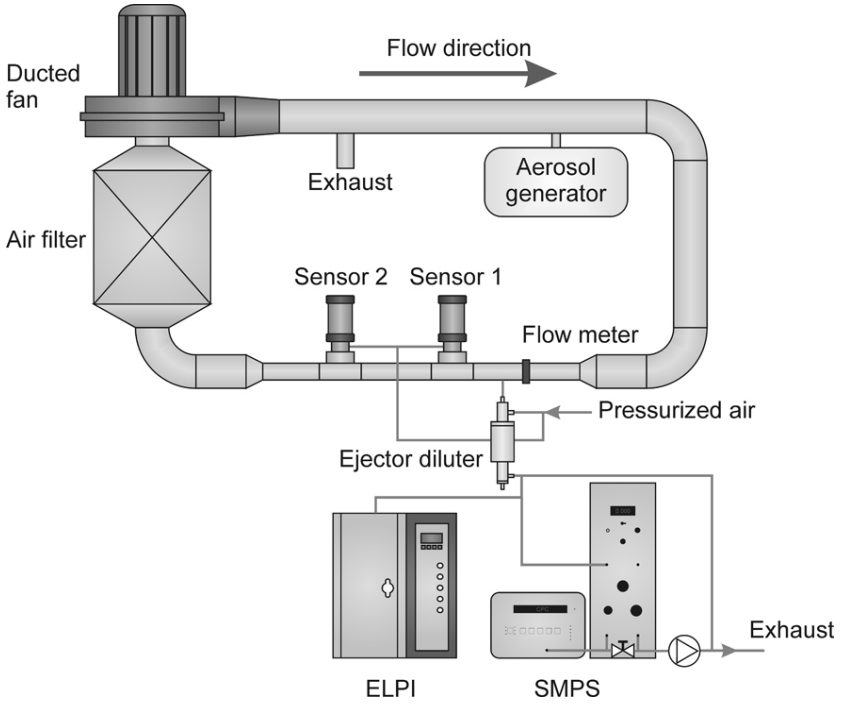

Fig. 2. Measurement set-up for laboratory tests. The DOS aerosol used in the tests was generated with a condensation-evaporation generator. As reference measurement ELPI and SMPS systems were used.

ejector diluter with a dilution ratio of 10.5. As reference instruments an Electrical Low-Pressure Impactor (ELPI, Keskinen *et al*., 1992) and a Scanning Mobility Particle Sizer (SMPS, Wang and Flagan 1990) were used. With these instruments the number size distribution of the test aerosol could be monitored together with the total concentration. The SMPS system was run with flow rates of 0.6 L/min of aerosol and 6 L/min of sheath air, which gave the measurement size range of 10-420 nm. The operational size range of the ELPI system was 7 nm-10 μm. The sample time of the SMPS was set to 120 s, whereas the ELPI size distribution was saved with 1 s interval. The data from the sensors was also saved with 1 s interval. All tests were performed in normal laboratory conditions and temperatures.

The test aerosol was generated from dioctyl sebacate (DOS) with an evaporation-condensation generator (e.g. Liu and Lee, 1970). With the generator, the median size of the test aerosol could be adjusted from 40 to 120 nm, while the geometric standard deviation was typically around 1.5. An example of a normalized and averaged size distribution used in the measurements is shown in Fig. 3. The ELPI was used to monitor the stability of the test aerosol in real time during the measurements. The particle concentration in the test flow could be varied by controlling the flow rate of the generated aerosol into the test flow. The generated aerosol was fed to the system 4 m before the tested sensors. The Reynolds number in the test flow was 26000 at the minimum. This indicates a high turbulence level, ensuring a complete mixing of the test aerosol.

INSTRUMENT RESPONSE

The charge level of the particles as such is not detected, only the charge particles acquire and carry away from the probe is detected. Therefore the initial charge of the particles does not affect the measurement, as long as it is well below the level acquired inside the probe. The measured current is proportional to the particle flux through the sensor and the charge that particles acquire inside the charger. For a charging process

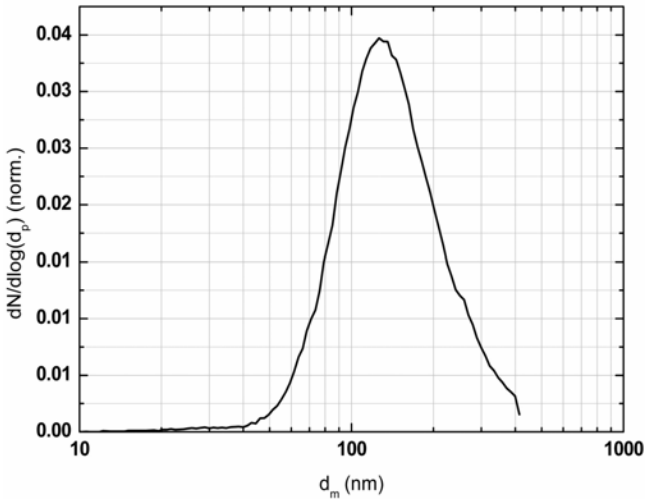

Fig. 3. Normalized average size distribution of the linearity test.

independent of the exhaust flow velocity and particle size, the output would be a direct measure of particle emission rate (#/s). However, the change in the charging efficiency with different flow velocities causes some nonlinearity to the sensor output compared to the actual particle flux in the measured flow. In addition, the amount of charge the particles acquire while travelling through the sensor depends on particle size through the so called active surface of the particles. That dependence has been used previously to measure the surface area content of aerosols by using conventional diffusion chargers. (Ntziachristos *et al.*, 2007).

Linearity

First of all we have to have a look on the sensor linearity to test the correct operation of the sensor. If the shape of the particle size distribution and the flow velocity do not change, the sensor output should be linear as a function of the particle concentration. To test this, the dependence of the sensor output signal on the particle concentration in the flow was measured with two flow velocities 10 m/s and 35 m/s. During the measurements only the concentration of the aerosol was varied, particle size distribution was kept constant and monitored with SMPS and ELPI. During the measurements the number median size of the aerosol distribution was 134 nm with GSD of 1.56. The measured sensor output signal was compared to the total number and surface area concentrations measured with SMPS in Fig. 4. From the comparison it can be seen that the sensor output is linear as a function of the particle concentration and the slope of the response curve depends on the flow velocity inside the channel and probe. The slight curvature seen on the number concentration correlation (left side of Fig. 4.) is caused by a small variation on the number median size of the distribution during the measurements. The effect of the variation does not show on the surface area correlation (right side of Fig. 4), since the particle charging and the sensor correlates better to the surface area concentration than to number concentration. Based on Fig. 4, we can use the ratio of the measured signal to the particle concentration in the following data analysis.

Effect of Particle Size and Flow Velocity

Because the sensor output signal originates from the charging of the particles with a corona discharge, both the properties of the particles (mainly the particle size) and their velocity through the charging region affects the measured signal. To understand the effect of these parameters, the sensor output signal needed to be studied with different particle sizes and flow velocities.

The effect of particle size could be studied using monodisperse particles, but in this case the required volumetric flow rates were so high that monodisperse particles could not be generated in sufficient concentrations for the measurement. Therefore the effect of particle size was studied with lognormal polydisperse distributions having different median diameters. The effect of particle size distribution with different flow velocities are shown in Fig. 5. In the figure, sensor output normalized with particle number concentration is plotted against the median size of the measured size distribution with different but constant flow velocities. The coordinate axis on the figure represents the response of the sensor to particle number concentration, and it has the same units as the charging efficiency of the ELPI (Keskinen *et al.*, 1992.).

Modeling of the Response

To gain understanding on the operation of the charger, a model is built based on the measurements. To explain the measured output signal, we have to look on the charging processes involved. Because the particle size range in this application is around 100 nm, the particle charging processes involved are primarily diffusion and secondly field charging. The total number of elementary charges per particle is approximated as the sum of the charges acquired by diffusion charging and field charging, i.e.

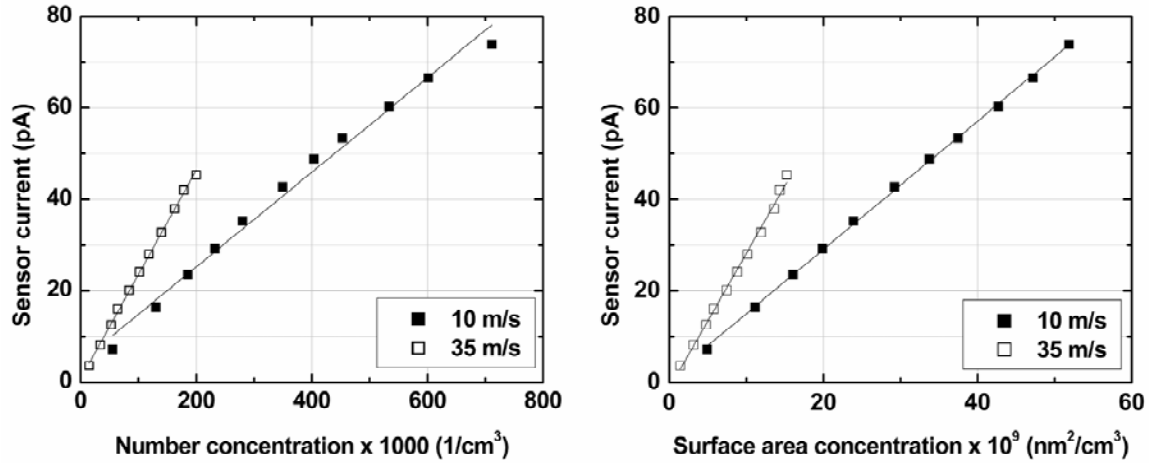

Fig. 4. Concentration dependence: Comparison of the sensor signal and total number concentration on the left and comparison of sensor signal and the total surface area concentration.

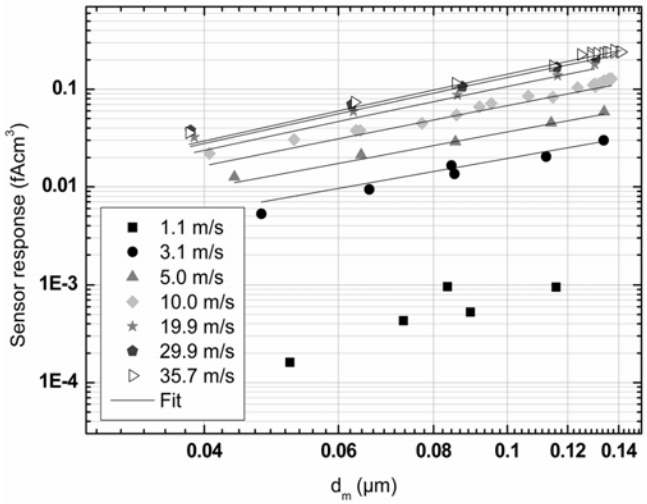

Fig. 5. Dependence of the sensor output on the median diameter of the size distribution. The sensor output is normalized to SMPS total number concentration for comparison. The solid line is simulated sensor output with fitted charger efficiency (Eq. (4)).

$$n = n_d + n_f = \frac{2pe_0 d_p kT}{e^2}\ln\left|\frac{d_p \bar{c}_i e^2 N_j t}{8e_0 kT}\right| + \left|\frac{3e}{e+2}\right|\left|\frac{E_{ave} d_{ppe_0}^2}{e}\right| \left|\frac{eZ_i N_i t}{4e_0\left|1+\frac{1}{4e_0}eZ_i N_i t\right|}\right| \quad (1)$$

where ε_0 is the permittivity of vacuum 8.85 × 10^{-12} F/m, ε is the relative permittivity of the particles 4, d_p is the particle mobility diameter, k is the Boltzmann constant 1.38 × 10^{23} J/K, T is the temperature of the gas 293 K, e is the charge of the elementary charge 1.602 × 10^{-19} C and $\bar{c}_i$ is the average thermal velocity of the charging ions 240 m/s, E_{ave} is the fitted average electrical field in the charging region and Z_i is the mobility of the charging ions 1.5 × 10^{-4} m²/s. The diffusion charging of the particles depends on the particle size and the $N_i t$ product, which is a product of the ion concentration and the residence time of the particles inside the charging region. Field charging depends also on the $N_i t$ product, but it also depends on the average electrical field inside the charging region and the permittivity of the particles.

The increase in the velocity of the measured flow should also increase the current which is measured from the sensor, since the amount of particles traveling through the charging region per second increases. However the flow velocity V_{flow} also affects the residence time t: an increase in the flow velocity reduces the residence time and the $N_i t$ product. Therefore the increase in the measured current is not linear to the flow velocity. The residence time depends on the flow velocity inside the charging region. Since the sensor probe can be considered as a porous medium in the flow, the flow velocity inside is smaller by a factor R. This gives for the residence time the approximate form shown in the Eq. (2)

$$t = \frac{L_{eff}}{V_{ch}}, \quad V_{ch} = R(V_{flow} - V_{\min}) \quad (2)$$

An artificial term V_{min} is added to the equation to simulate the fact that below a certain minimum flow velocity no charged particles can exit the charger, i.e. all of the particles are collected inside the charger by electrical forces. L_{eff} is the fitted effective length of the charging region in the flow direction. The ratio R describes the ratio of flow velocities inside and outside of the charging region. Theoretical calculation of the ratio R ("effective porosity") gives a value of 0.29. The calculation has been performed according to the following principles and assumptions: Since the detection volume is inside of two perforated cylinders, the aerosol flows through four perforated plates – two plates prior and two after the charging region. Because of this the total pressure drop between the inlet and outlet faces of the sensor is the sum of the pressure drop of each perforated plate. Following estimations and approximations have been made: 1) The curvatures of the plates are assumed to be negligible in the streamlines following through the charging region. 2) The discharge coefficient C_d of each hole of the perforated walls is assumed to be 0.7. 3) The flow field reaches a fully developed state prior to each wall.

The resulting response of the charger, E_{ch}, can be written as

$$E_{ch} = \frac{1}{4}pd_{duct}^2 R(V_{flow} - V_{\min})ne \quad (3)$$

where the diameter of the flow channel is d_{duct}, R is the ratio of the flow velocity inside the charging region and e is the elementary charge. For practical use of the sensor, the output signal should be converted to a relevant concentration or emission value. Presented model can be used for this purpose, if the flow velocity and size distribution of the measured aerosol is known.

As seen in Fig. 5 the response of the particles increases with increasing particle size, which is expected since charging efficiency increases with increasing particle size. The response also increases with the increasing flow velocity. This is attributed to the fact that the amount of particles passing through the sensor increases increasing the charge carried away by the particles. The actual charging efficiency for individual particles decreases with increasing flow velocity, since the residence time inside the charging region decreases.

We can use the theoretical approach presented to build a fit for the response of the instrument. The fit can then be used to predict the response of the instrument for different aerosol size distributions. The output current of the sensor is the integral equation of the response of the charger and the size distribution as follows:

$$I_s = \int \mathrm{E_{ch}}(\mathrm{d_p}, \mathrm{V_{flow}})\,\mathrm{N}(\mathrm{d_p})\,\mathrm{dd_p} \quad (4)$$

The term $N(d_p)$ is the number concentration as a function of particle size, E_{ch} is the response of the charger as a function of particle size and flow velocity as derived in Eq. (3). The fit is constructed so that the parameters for the theoretical model are fitted to minimize the difference between the measured current and the current simulated from the measured size distribution using the theoretical model.

Now selected parameters from the equations of the average charge number (Eq. (1)) are fitted so that the simulated currents agree with the corresponding measured currents. Parameters used for the fitting are ion concentration, average electric field, minimum flow velocity and effective length of the charging region. The fitted parameter values are collected to Table 2. It has to be remembered that values are not thought to be physically accurate; they are just values that give the best prediction for the operation and response of the instrument. Even so, all of the fitted values are realistic and feasible for the used construction.

Table 2. Fitted parameters to particle charging model.

Description	Symbol	Value
Effective length of the charging region	L_{eff}	6.8×10^{-3} mm
Average electric field	E_{ave}	2.07×10^{5} V/m
Ion concentration	N_i	1.28×10^{15} 1/m³
Minimum flow velocity	V_{min}	1.6 m/s

The resulting response with different flow velocities are plotted to Fig. 6. All of the measurements for this study were used to generate the fit. In Fig. 7, the simulated sensor outputs using the fit are plotted against corresponding measured values. As can be seen from the figure the fit predicts the measurements nicely, suggesting that the fit is reliable and can be used to predict results. Size dependence of the response predicted by the fit is also plotted with solid line in Fig. 5.

The fit can be used to estimate the response of the instrument for different size distributions, as plotted in Fig. 8. Only number concentration response is shown in the figure, but mass concentration and number or mass emission rate responses could be easily constructed for any given aerosol size distribution. With the aid of the obtained response, the current signal from the sensor can be converted to a number or mass concentration value, if the flow velocity and properties of the size distribution of the measured aerosol are known. The emission rate responses do not depend on the flow velocity of the measured flow as much as the number or mass concentration response. This makes it possible for a narrow flow velocity range to convert the sensor output to an emission rate value by using a simple conversion factor without the need of measuring the flow velocity.

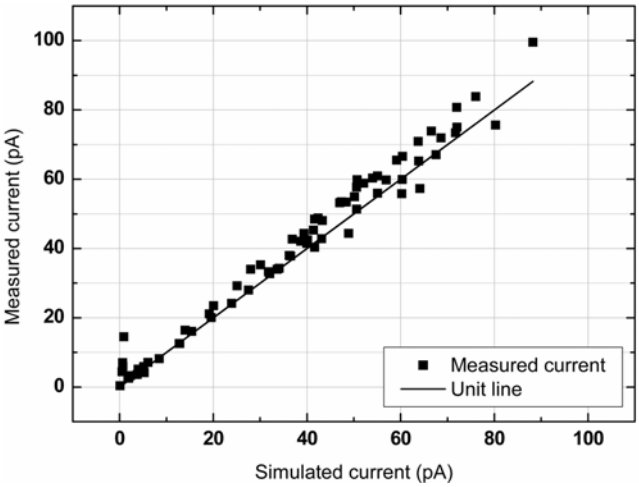

Fig. 7. Simulated sensor output as a function of the measured output.

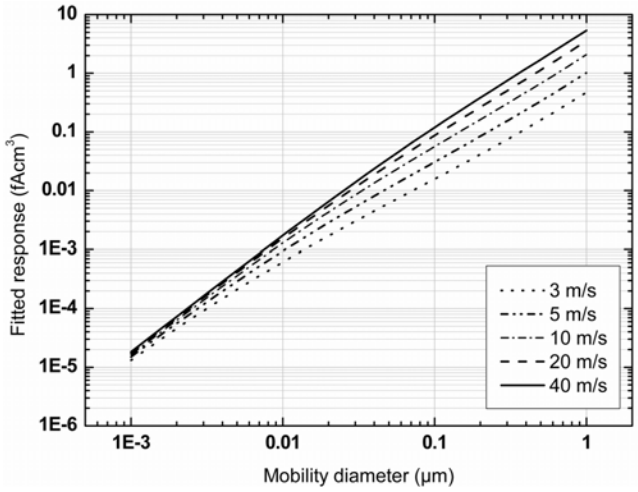

Fig. 6. Fitted charging efficiency curves for the sensor with different flow velocities.

TEST MEASUREMENTS WITH DIESEL EXHAUST

The designed sensor is intended to measure the particle concentration of a diesel engine exhaust. Moreover, the whole sensor is intended to be mounted so that the raw exhaust gases flow through the sensor probe. To test the sensor design, diesel exhaust measurements were made. Fig. 9 demonstrates the operation of the sensor in a real life measurement. The figure shows how the particle mass concentration inside the exhaust line changes during an engine test cycle. The measured sensor signal is first converted to a number concentration value with the aid of Eq. (4) by assuming the particle size distribution to be constant with a median size of 80 nm and a GSD of 1.75. After that the number concentration was converted to a mass concentration.

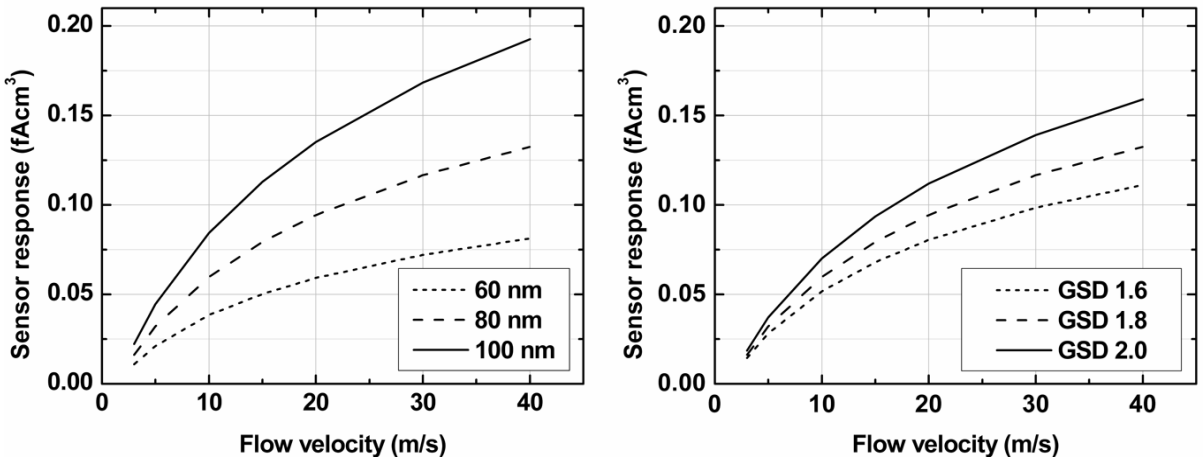

Fig. 8. Sensor response for different lognormal size distributions as a function of the flow velocity. On the left the effect of the median diameter with constant GSD of 1.80 and on the right the effect of the GSD with a constant median size of 80 nm is shown.

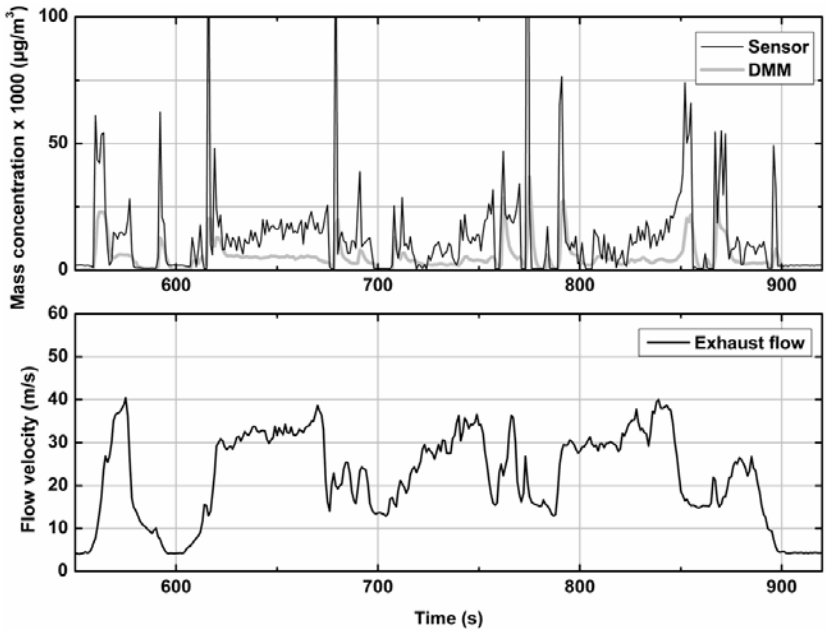

Fig. 9. Mass concentration of a diesel exhaust during a test cycle measured with ETaPS sensor and DMM together with a flow velocity inside the exhaust line.

The effective density of the particles was assumed to obey a fractal law, with a mass fractal dimension of 2.6 (e.g. Virtanen *et al*., 2002). The resulting mass concentration is plotted to Fig. 9 as a function of time. Corresponding mass concentration values obtained with a Dekati Mass Monitor (DMM-230, Lehmann *et al.*, 2004) are shown for comparison.

It can be seen from Fig. 9, that the mass concentration measured with the sensor follows the reference measurement. We can see that the emission peaks from the changes in the engine load are much sharper in the ETaPS data than what measured with the DMM. This shows the effect of slower response time of the dilution system used in the DMM measurement. ETaPS can distinguish the short concentration peaks during engine loading transients, while the diluter-DMM combination smoothes the peaks significantly. Fig. 10 shows a correlation plot, where the mass concentration measured with the sensor is plotted against the reference measurement. Since the instruments have a different time responses, an additional time constant of 1.8 seconds was artificially added to the ETaPS sensor signal to have similar time responses in both instruments. The correct time alignment of the data was found by cross correlation. Finally a time constant of 10 s was added to both measurement data to add averaging and to reduce the effects of timing misalignments in the sensor and flow velocity measurements. Then the correlation between the instruments was calculated and the resulting correlation plot is shown in Fig. 10. With the diesel engine measurements the mechanical structure withstood the extreme conditions inside the exhaust line. The operation of the sensor has been successfully tested in temperatures ranging up to 400°C with a flow velocity ranging up to 50 m/s. Although the operation times of the sensor depends on the concentrations measured, with modern diesel engines having low emissions the sensor can be operated without need for cleaning.

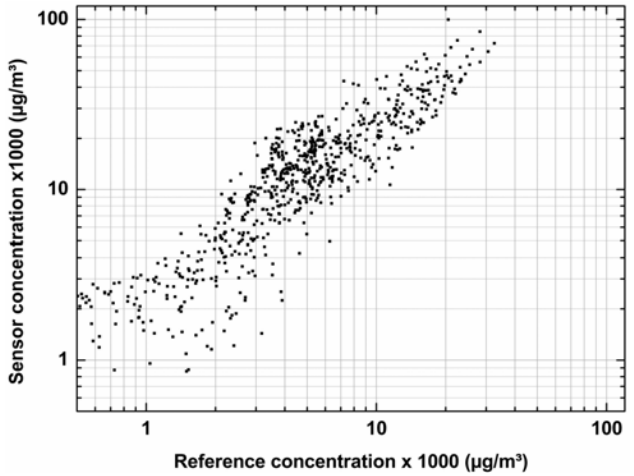

Fig. 10. Mass concentration measured with the sensor as a function of reference mass concentration measured with DMM. The minimum value of the y-axis is limited to the detection limit of the sensor, caused by the data logging and selected sensor sensitivity range for the measurements.

DISCUSSION AND CONCLUSIONS

The presented sensor design allows in situ measurement of aerosol concentration without any dilution or sampling systems. This allows faster response time and simpler measurement setup compared to traditional aerosol instrumentation. With the sensor events such as engine start ups and sudden changes of engine load can be easily monitored. The measured particles are not collected by the sensor allowing longer operation times without service.

The response of the sensor depends primarily on the particle flux through the sensor and the presented theoretical model can be used to predict the response of the instrument in different measurement conditions. If the size distribution of the measured aerosol is known, the model can also be used to convert the measured sensor signal into a concentration value. The model is useful in predicting the operation of the sensor and it can be used as an aid when the measurement principle is used in other applications. Depending on the application, the quantity that is sought after can be different. It can be for example number or mass concentration or active surface of the particles.

In the studied configuration, the response of the sensor is affected by the flow velocity in the measured exhaust flow. This is a trade off with the simplicity of the measurement set-up. This same type of measurement method can also be used with a forced constant flow system to overcome this dependence of the flow velocity. The operational concentration range of the sensor is 10^4-10^8 1/cm³ with a flow velocity range of 3-50 m/s. The operation of the designed sensor was tested successfully in the conditions of the exhaust line of a running diesel engine.

The calibration measurements presented here were made at room temperature. In order to increase the accuracy in diesel exhaust measurements, the effect of the elevated temperature of the exhaust gases must be included into the developed model. In the exhaust gas measurements, although the effect of temperature was not taken into account, the correlation in the mass concentration of the sensor to the reference measurement was good.

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