An electrical sensor for long-term monitoring of ultrafine particles in workplaces

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Abstract. Pegasor Oy Ltd. (Finland) has developed a diffusion charging measurement device that enables continuous monitoring of fine particle concentration at a low initial and lifecycle cost. The innovation, for which an international process and apparatus patent has been applied for, opens doors for monitoring nanoparticle concentrations in workplaces.

The Pegasor Particle Sensor (PPS) operates by electrostatically charging particles passing through the sensor and then measuring the current caused by the charged particles as they leave the sensor. The particles never touch the sensor and so never accumulate on its surfaces or need to be cleaned off. The sensor uses an ejector pump to draw a constant sample flow into the sensing area where it is mixed with the clean, charged pump flow air (provided by an external source). The sample flow containing charged particles passes through the sensor. The current generated by the charge leaving the detection volume is measured and related to the particle surface area. This system is extremely simple and reliable – no contact, no moving parts, and all critical parts of the sensor are constantly cleaned by a stream of fresh, filtered air. Due to the ejector pump, the sample flow, and respectively the sensor response is independent of the flow and pressure conditions around the sampling inlet.

Tests with the Pegasor Particle Sensor have been conducted in a laboratory, and at a workplace producing nanoparticles for glass coatings. A new measurement protocol has been designed to ensure that process workers are not exposed to unusually high nanoparticle concentrations at any time during their working day. One sensor is placed inside the process line, and a light alarm system indicates the worker not to open any protective shielding or ventilation systems before concentration inside has reached background levels.

The benefits of PPS in industrial hygiene are that the same monitoring technology can be used at the source as well as at the worker breathing zone. Up to eight sensors can be installed in series for centralized monitoring of the whole process in real time.

1. Introduction

Health risks caused by particle exposures at workplaces are typically underestimated. Epidemiological studies conducted during the last 15 years have yet established the role of particulate air pollution as a
risk factor for not only respiratory but also cardiovascular diseases [1]. Recently, researchers have linked particle exposure also e.g. with diabetes and rheumatoid arthritis [2, 3]. Together with improved exposure assessment methods, risk estimates have gradually increased. Highest risks are associated with long-term (years) exposures, but even very short-term exposures may affect health [4].

There is evidence that all major size fractions of particles – ultrafine, fine and coarse – have adverse effects on health. However, ultrafine particles have some unique properties compared to larger particles: very high number challenging macrophage based immune system, large surface area enhancing chemical reactions, and extremely small size enabling efficient penetration into the body [5]. Thus, there are concerns that the expansion of nanotechnology and rapidly increasing nanoparticle production will increase the health risks at workplaces [6].

Particle exposures encountered at work are often several magnitudes higher than elsewhere [7]. In contrast to urban environments, particles are yet rarely monitored at workplaces. This is mainly due to the high costs of monitoring. High spatial variability of particles, especially coarse and ultrafine, further complicates exposure assessment, because ideally particles should be monitored simultaneously in multiple locations. The electrical sensor presented here enables particle monitoring at low initial and maintenance costs using several sensors.

2. Pegasor Particle Sensor
The patented [8] Pegasor Particle Sensor (PPS) operates by electrostatically charging particles passing through its body and then measuring the current produced by the charged particles as they leave the sensor. The basic principle of directly measuring the current escaping with charged particles was first described by Lehtimäki [9].

![Figure 1. The basic principle of the electrical aerosol sensor based on the measurement of the escaping current.](image)

The particles are charged by ions generated by a corona discharge, which is generated around a sharp tip at high voltage (Figure 1). After charging, the particles are neither collected on any filter nor accumulate on any part of the sensor. However, as charged particles leave the sensor, they produce an electrical current escaping the Faraday cup. Measurement of this current is proportional to the particle concentration.

Even minimal soot deposition on critical surfaces, as electrical insulators, may cause leakage currents altering the measurement result. Further, the contamination of high-voltage insulators reduces the discharge voltage, preventing ion production. The discharge may also be fused by contamination of the corona tip. In order to get around these issues, the sensor protects all sensitive surfaces from soot deposition. Figure 2 shows how this is achieved. Clean filtered air is fed through an air nozzle, where the corona tip is located. In the area of high flow velocity, the corona discharge effectively generates ions at sufficiently low voltage. The nozzle discharges sonic flow functioning as a “pump flow” of an ejector. The resulting ejector pump sucks the sample flow from the inlet. The charged pump and sample flows are mixed prior to entering the ejector throat, which allows efficient particle charging. The ion trap followed by the ejector throat removes the free ions, so that only charged
particles leave the sensor with the sample flow. The functional part of the sensor taking care of the charging, ion trapping and sample flow guiding are electrically insulated. The electric current from the insulated part to ground is measured by an electrometer. This measured current represents the charging rate of the particles in the sample flow.

The sensor electronics contain a wide-dynamic range electrometer measuring the current carried by charged particles and a high-voltage unit powering the corona discharge with constant current. The system control and data processing and transfer are performed by a digital control unit. In addition to the pure processing of the measurement signal, the control unit has also functions to diagnose the operating condition and cleaning needs of the sensor. The sensor data and control signals (RS485 bus) are transferred through an interface unit to and from a laptop computer (USB bus). Optionally the sensor can be used as a stand alone instrument without PC using a 4-channel, 20-bit digital-to-analog conversion unit. The time response of the current sensor version is 0.3 s, and data sampling rate is 10 Hz. Specialized sensor software enables the sensor control and data logging on a PC. It contains basic data processing functions (user defined time constants and data averaging), as well as the graphical data presentation and data storage.

3. Experimental setup

3.1. Comparison to other methods

The performance of the Pegasor sensor was studied as a part of the measurements which were focused on the behaviour of nanosized particles generated through laser ablation. These measurements were made at VTT Lappeenranta (Factory of the future) by using a femtosecond (fs) laser workstation. During the experiments nickel disc target was continuously scanned with a constant power laser beam and the released particles were captured with an exhaust hood. The principle of the set-up used in the study is illustrated in Figure 3.

Figure 2. Sensor schematic. The air jet ionized in the corona discharge functions as a pump flow of an ejector. The ejector draws the sample flow, and the particles are charged prior to the ion trap. The inner part of sensor is electrically isolated, and the current measured from it equals the charging rate of particles exiting with the outlet flow.

Figure 3. Principle of the measurement system used when studying nanoparticles generated by the fs laser work station.
The purpose of these measurements was to provide information about the behaviour of nanoparticles generated by fs laser work station, and clarify how the local exhaust system can be utilized to prevent nanoparticles from dispersing into the workplace air. The particle measurements were made with a system which included ELPI (Electrical low-pressure impactor) equipped with a sampling system, which was used to continuously monitor particles from three sampling points. Two of the sampling points were located in the vicinity of the nickel disc processed by the laser beam and the third sampling line was used to sample air from the exhaust duct. Besides ELPI, the quality of air was monitored with Pegasor sensor, DustTrak aerosol photometer and electrical aerosol detector (EAD).

The major aim of experiments with different aerosol sensors was to demonstrate how they can be used to detect possible emissions of engineering nanoparticles from a work process. In many practical applications, the existing background concentration of ultrafine particles is so high that nanoparticle emissions may contribute only slightly on the total concentration. The sudden nanoparticle release was simulated here by switching the local exhaust system off for a short period of time.

3.2. Trap voltage scanning
An interesting feature in the Pegasor sensor is the possibility to modify its characteristics by varying the trap voltage, i.e. the voltage which is primarily for preventing ions from escaping the sensor. This means that by increasing the trap voltage to a certain level, particles below the corresponding size limit can be collected before they leave the sensor. Thus, these particles do not contribute to the output of the sensor. It is even possible to scan the trap voltage in a wide range in such a way that the relationship between sensor output and trap voltage can be determined. In principle, this relationship includes information about the particle size distribution.

The trap voltage scanning was tested by measuring the sensor output vs. trap voltage for three polydisperse aerosols. The test aerosols were generated with an aerosol atomizer from very diluted solutions of DEHS in isopropanol. The count median particle sizes of these aerosols were 8 - 15 nm.

The relationship between sensor output and trap voltage was also studied at the laser work station. In the first phase, trap voltage scanning was made when measuring the background aerosol. The corresponding experiment with trap voltage scanning was also made from the exhaust air. In this case the measured aerosol represents the nanoparticles generated by the laser ablation.

3.3. Feasibility study
The feasibility of the method for monitoring simultaneously particle concentrations at a source and in the breathing air was evaluated at an industrial facility producing nanoparticles for glass coating. One sensor was placed inside the nanoparticle production chamber, and another one in the working space.

4. Results

4.1. Comparison to other methods
Figure 4 shows the responses of the ELPI and Pegasor particle sensor. In this figure the total current collected by the ELPI impaction stages are shown together with the sensor output. This result illustrates that responses of ELPI total current and Pegasor sensor are identical. This is an expected result because the particle charging in both devices is accomplished with the unipolar diffusion charging process. This result also indicates that the sensor responded quickly to the nanoparticle release caused by the switch off of the local exhaust.
The corresponding comparison between the electrical aerosol detector (EAD) and Pegasor sensor is shown in Figure 5. Also in this case the devices, the principle of which is based on the same physical process, provide almost identical responses. However, the output of the EAD also contains additional concentration peaks. These peaks could be due to different locations of the devices, i.e. EAD may have been impacted more by the sporadic nanoparticle puffs from the laser processing.

**Figure 4.** ELPI total current and the Pegasor output voltage. Effect of switching off the local exhaust.

**Figure 5.** Responses from the EAD and Pegasor sensor. Effect of switching off the local exhaust.

The response of the Pegasor sensor was also compared with the aerosol photometer (DustTrak), which is a widely used tool in industrial hygiene. In this case the two devices provide quite different responses (Figure 6). The concentration indicated by DustTrak increases after switching off the local exhaust. However, the decrease of the concentration (after the local exhaust was switched on) is quite
modest indicating that the output of the DustTrak may be affected by some other particles from the other processes in the building.

![Graph showing DustTrak output and Pegasor sensor output](image)

**Figure 6.** Responses from the DustTrak aerosol photometer and Pegasor sensor. Effect of switching off the local exhaust.

4.2. Trap voltage scanning

The results shown in Figure 7 illustrate that the aerosols with different size distributions provide totally different characteristics. The lower the count median particle size is the steeper is the effect of trap voltage.

![Graph showing sensor output vs. trap voltage](image)

**Figure 7.** The normalized sensor output vs. trap voltage characteristics measured with three nanosized test aerosols (#1: cmd=15 nm, #2: cmd=11 nm, #3: cmd=8 nm).
Measurements of background aerosol at the laser work station (Figure 8) show that the sensor voltage decreases less steeply with trap voltage than in the case of very fine laboratory aerosols (Figure 7).

**Figure 8.** The normalized sensor output vs. trap voltage characteristics measured from the background aerosol.

The corresponding experiment with trap voltage scanning was also made from the exhaust air. In this case the measured aerosol represents the nanoparticles generated by the laser ablation. The results (Figure 9) show that the generated aerosol is somewhat finer than the aerosol found from the surrounding air.

**Figure 9.** The normalized sensor output vs. trap voltage characteristics measured from the exhaust air. The average from the results with background aerosol included.
4.3. Feasibility study
Median (max) concentration inside the nanoparticle production chamber was 0.90 (1000) mV and outside 0.42 (2.1) mV. Production cycles were reflected as very high but short-term concentration peaks within the chamber (Figure 10).

New measurement protocol was developed where background level is measured at the workers’ breathing zone for one week continuously. The average of this measurement period is used as the zero level – green light indication. Light indicating alarm is used to inform the worker, if the average background level is exceeded five times (yellow light) or ten times (red light). One sensor is placed inside the process line to indicate the worker not to open any protective shielding or ventilation systems before concentration inside has reached background levels.

![Figure 10. Output voltages of Pegasor sensors placed within and outside a nanoparticle production line (note the very different scales of the axes).](image)

5. Conclusions
Diffusion chargers have been investigated for many years [10], but it is only in the last few years that the available technology and the technical requirements of various applications have come together to offer a practical solution. The electrical sensor developed by Pegasor Oy Ltd. (Finland) enables particle monitoring at low initial and maintenance costs using several sensors. Clean air is utilized both for the charged pump flow and for cooling and shielding the critical insulators. As a result, all contamination-sensitive parts are shielded by clean air flow. The fact that the ion-containing pump flow is mixed extremely rapidly prior to the ejector throat enables efficient particle charging in minimal volume. This leads to low internal gas volume in the sensor and rapid response time. Due to the ejector pump, the sample-flow rate and sensor response is independent of the exhaust flow conditions around the sampling inlet.

Concentrations measured with the Pegasor sensor closely followed those measured with an electrical low-pressure impactor and an electrical aerosol detector. Concentrations differed more from the results of a photometer, most likely because Pegasor sensor is more sensitive to smallest particles.

Our results within a nanoparticle production facility demonstrated the usefulness of the sensor, together with a carefully designed monitoring program, in ensuring that process workers are not exposed to unusually high nanoparticle concentrations at any time during their working day. High exposures to nano-sized particles are common in a wide variety of occupations. Particle monitoring in
nanoparticle industry may be considered especially important because exposure is not necessarily associated with odorous volatile components which enable identification of exposure to many other types of ultrafine particles such as welding fumes.

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