Testo
white paper

Be sure.

Particle measurement for practical users: classifying particles, understanding measurement methods and selecting measuring instruments

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Foreword

Imagine you are lying on a beach in the sun and letting the sand trickle through your fingers. Fine sand has an average grain diameter of 0.5 mm/500 µm. The ratio of a grain of sand to a particle with a size of 0.5 µm/500 nm that is too small to be detected by the naked eye roughly corresponds to that of a rock with a diameter of 5 m to this grain of sand. This gives you an idea of the proportions we have to deal with when measuring particles.
It is necessary to know the mass or size distribution of particles in order to be able to evaluate their behaviour.

There are a variety of measurement methods to do this, which depend not least on the properties of the particles. In this white paper, we want to provide you with basic information about the methods of particle measurement which are used at Testo and at the same time present our particle measuring instruments to you. You will find information and application examples here concerning

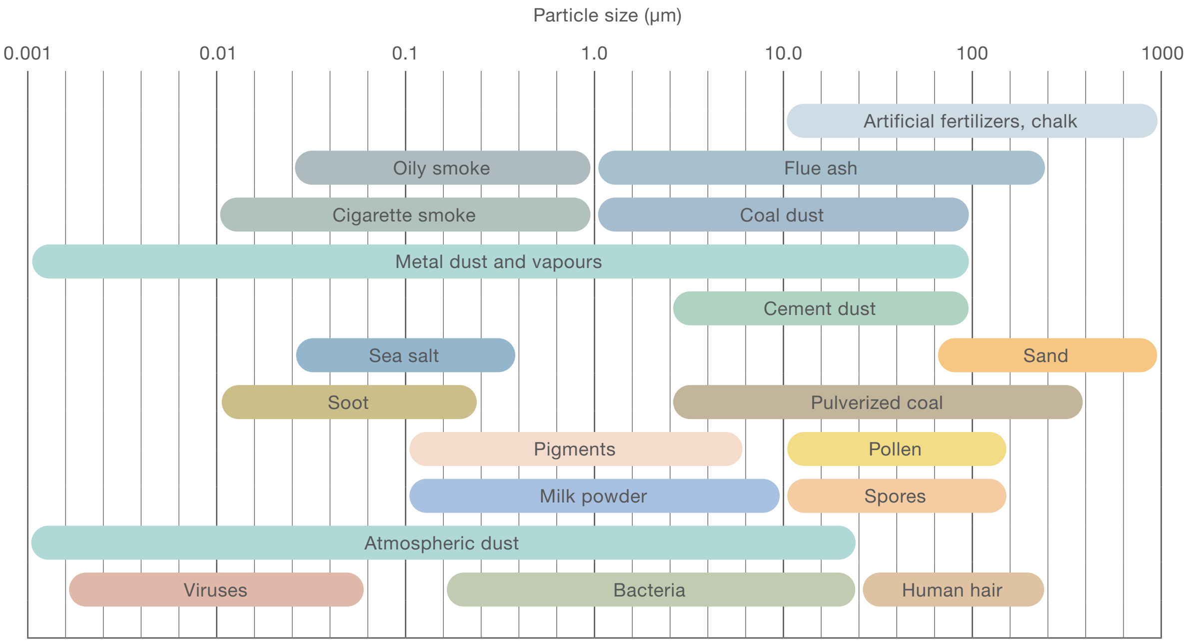
- testo 338, the degree of blackening measuring instrument for flue gases from diesel engines
- testo 380, the fine particle measuring instrument for chimney sweeps according to the 1st German Federal Immission Control Ordinance (BImSchV)
- testo DiSCmini, the handheld measuring instrument for measuring the number concentration of nanoparticles
- testo NanoMet3, the PEMS (Portable Emission Measurement System) for measuring nanoparticle emissions on vehicles.

Do you have further suggestions or would you like to see more points added? Just let our Testo project team know about this. We will be happy to take your advice and suggestions into account in the subsequent versions of this white paper.

Introduction to particle measurement at Testo

Particle measurement in general

Particles are parts of a heterogeneous mixture of substances which are clearly differentiated from the surrounding medium – a gas, such as air, or a liquid. If this mixture of substances is composed of gas and the particles are floating in it, then this is an aerosol, whereas a suspension refers to a mixture of liquids and solids.



A comparison of the sizes of selected particles

At Testo, we deal with the measurement of aerosols – with the particles which are all around us in the air or are emitted into it.

Particles of this kind may be of a natural origin or be a result of human activity. Sand particles which are stirred up and scattered by the wind, spray which occurs when there is stormy weather on the coast, ash and soot which are carried by the wind for kilometres when there are forest fires and volcanic eruptions – particles have been emitted since time immemorial. Only our ancestors were not aware of what dangers many of these particles entail. So, an examination of the glacier mummy Ötzi showed that a large number of particles generated by combustion had been deposited in his lungs due to sitting beside an open fire every evening [1].

It is mainly road traffic, industrial processes and the heating of our homes that are responsible for the fine particles that now occur in towns and cities. On the other hand, the sea air with its salt particles shows that not all emitted particles necessarily have negative effects on our health.

Unfortunately, substances which are generated by humans and present a risk to health now constitute a large proportion of the particles in particulate matter [2].

Why do we measure particles?

A variety of reasons can be identified for particle measurement. In addition to controlling particle exposure due to particulate matter in inner cities, particles are also measured to assess the efficiency of combustion processes or to enable statements to be made about material properties. There are several reasons and we have identified the following three for our measuring instruments.

[1] https://www.researchgate.net/publication/267237729_EFTEM_tells_us_what_the_Tyrolean_Iceman_inhaled_5300_years_ago)

[2] https://www.umweltbundesamt.de/themen/luft/wirkungen-von-luftschadstoffen/wirkungen-auf-die-gesundheit#textpart-1

Health aspects

We do almost everything we can nowadays to maintain our health. We are aware of the need to nourish ourselves properly, do sports and avoid activities that affect health. Those are the obvious factors.

However, when we turn to fine particles with their maximum particle size of 10 µm, then it quickly becomes clear that this health risk cannot be established by glancing out of the window every morning. While particles with a size of 10 µm – still five or eight times thinner than a human hair – are already filtered out by the upper respiratory tracts and do not get into the bronchia, smaller particles with a size of 1 µm do get that far. Ultra-fine particulates made up of nanoparticles with a size of less than 0.1 µm are not only deposited in the pulmonary alveoli, but also get into the bloodstream. This means they can be transported to every organ and be deposited there [3]. The surfaces of particles are often wetted with other substances. If these include harmful hydrocarbons, fine particles can present a major risk to health.

Reason enough to curb fine particle emissions and to verify successes through regular measurements of concentrations.

Machine efficiency and process monitoring

We have already identified the heating of our living spaces as a source of fine particles. This reveals a quandary: On the one hand the emission of particles has indeed been reduced by optimizing combustion processes, but on the other hand this has led to more small particles – particles which have an impact on the fine particle balance sheet. In order to be able to design these heating systems to be even more environmentally friendly, the possible emission of particles not only needs to be checked during the new development and optimization of these systems.

Compliance with emission limit values must be regularly scrutinized.

This consideration also underlies regular checks of particle emissions from vehicles. In this respect, diesel engines, which are often decried as “dirty polluters”, are often unjustifiably criticized. It is indeed important to regularly check that a particle filter is working properly. However, when a filter is working properly, a modern diesel engine now emits fewer nanoparticles than the amounts found in the ambient air on an averagely busy street. In this area, it is more a case of GDI petrol engines as originators of ultra-fine particles constituting a health risk and in future likewise needing efficient filters for treating exhaust gas, along with regular checks [4].

Material properties

It is not only the quantity of particles that is consistently the reason for particle measurements. There are also measurement methods which are intended to provide information about the qualitative properties of the particles. For example, if you let particles grow in a process (granulation), then speed of growth and achievable particle size have an influence on factors like particle stability or speed of particle decomposition in liquids.

[3] https://pubs.acs.org/doi/abs/10.1021/es0522635

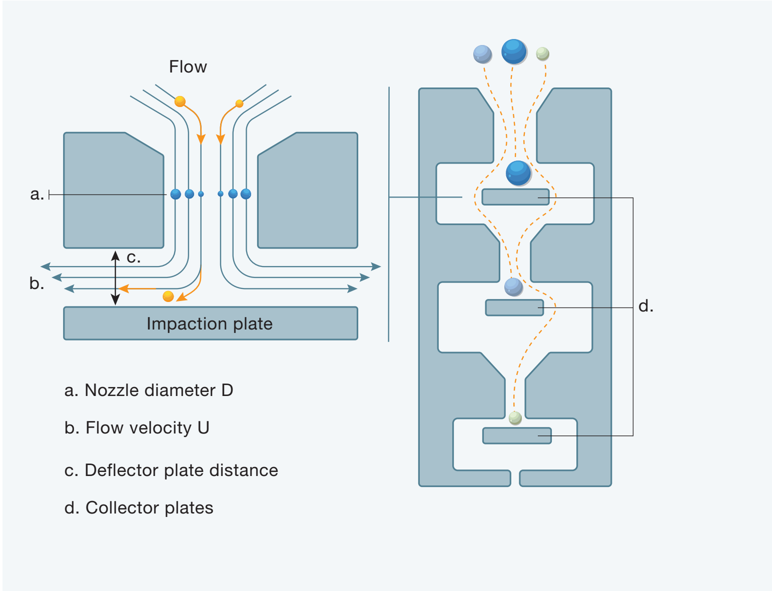
[4] https://www.zeit.de/mobilitaet/2017-02/feinstaub-auto-partikelfilter-abgas-diesel-benziner-eu/seite-2

How do we measure particles?
If the measurement is limited to the particles themselves and the intention is not to determine the material composition, three properties are of interest: the weight, number and size of the particles.

Particle weight

In conjunction with particle analysis, gravimetric measurement, that is the determination of the weight of particles, is probably the most well-known measurement method. Even in areas where modern methods have been known about for a long time, the weighing of laden filter sheets continues to be cited as the reference method for the determination of particle masses.
This involves the filter medium being prepared in a laborious process (drying, weighing) and inserted into a filter holder. After a defined volume of a gas laden with particles – the sample – has been fed through the filter paper, this is again dried and weighed. The difference in weight thus corresponds to the particle mass which has been filtered out of the sample.

If it is a case of the mass-related recording of different particle sizes of a mixture, then sieves can be used in the analysis. After they have been weighed, they are stacked on sieve towers in decreasing mesh sizes. After a weighed quantity of the screening material has been deposited, this tower is made to vibrate and the sieves are weighed again once the process has ended. The particle mixture can thus be classified according to size. Depending on the initial substance and the mesh size of the sieve, there are wet sieves or air jet sieves which allow the classification of smaller particles down to particle sizes of just a few µm.



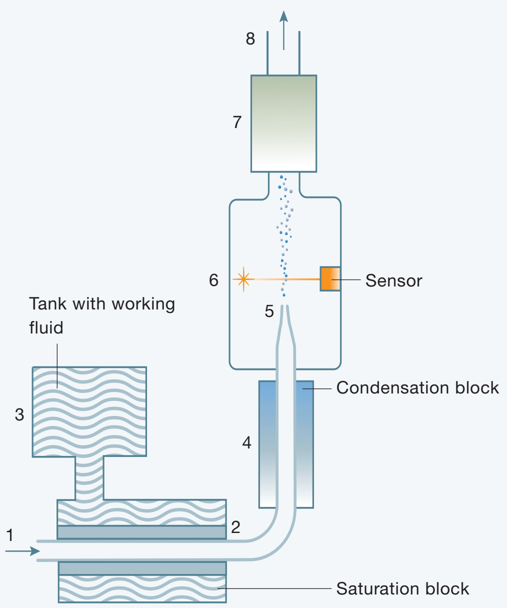
How a cascade impactor works

The mass inertia of the particles is used in gravimetric measurement with impactors. These are fed by an airflow vertically onto a deflector plate where the airflow is deflected at right angles. If the mass of the particle is great enough, it cannot follow the air flow and hits the deflector plate. The particles are deposited here and weighed after the measurement is completed. In order to be able to adjust to the behaviour of the particles, various materials are used for the surfaces of the impactors. They can for instance be provided with aluminium or plastic films. Cascade impactors involve impactors with different separation capacities being set up in sequence. This enables the particle masses to be allocated to different size categories.

Particle number

In the world of nanoparticles, that is with particles that are under 100 nm in size, classification according to weight is no longer possible. Here, particles are counted and classified into size categories. In the nano world, we make use of the special physical properties of the particles to enable the analysis of their number concentration.

A condensing particle counter takes advantage of the effect of the condensation of gases on solid particles. The air flow laden with particles is fed through a heated saturation block (1) where a liquid is evaporated, thus creating a supersaturated atmosphere (2).



How a condensing particle counter works

During the subsequent cooling in the condensation block, the liquid condenses onto the particles contained in the gas flow (4). The drops that arise (5) can be counted using an optical detector (6). Benzene, isopropanol or also water are for example used as liquids (3) depending on the field of application. After the measurement, the condensed liquid is separated out of the gas flow along with the particles (7) and the sample gas, in our case the used air, comes out (8).

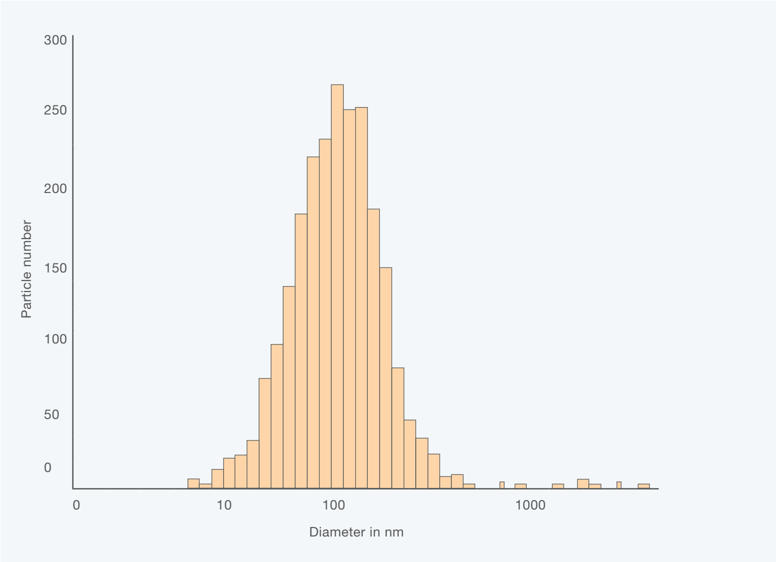
The optical detectors which are used operate according to the light-scattering principle. This means that the sample is fed through a light beam and a scattering of this beam occurs due to the particles contained in the sample. This scattering is detected via an optoelectronic sensor and, once the signal has been analyzed, the result provides information about the number concentration of the particles. Laser scattering normally only works for particles which are larger than nanoparticles. You get round this limitation here by enlarging the particle diameter in the condensation block (4).

No matter how small particles are, they can take on and transport loads and then relinquish them again. We make use of this property in diffusion charging. The DiSC sensor works according to this principle. It comprises a charging chamber where the particles are given a charge in an electrical alternating field and one or more stages in which the charging amount is detected using a sensor. When working with these sensors, you are not obliged to use any further operating materials. Radioactive radiation sources for the neutralization of the charge of the analyzed particles are not required either. That enables the construction of sensors which are also very suitable for mobile use.

Particle size

SMPS (Scanning Mobility Particle Sizers) are for example used for investigating the particle size distribution of nanoparticles. The mobility of the nanoparticles, that is the intensity of the particle movements caused by Brownian motion, increases as the particle size decreases. This means that the smallest particles are the most agile and move in the most intense way.
We make use of this property in the analysis. If you feed a gas sample laden with nanoparticles along a negatively charged high-voltage electrode, the particles will be classified. The monodisperse particle category which thus occurs is removed and fed to a particle counter. This means you can record the number of particles of a size category.

If the voltage of the electrode can be changed, there is the possibility of classifying and counting the particles that are in the sample step by step. If you enter the measuring values obtained in this way into a diagram, you get the particle size distribution found in the sample.
The particle size can also be measured using an electron microscope. This method is indeed very laborious, but the visualization of the particles gives you a good impression of their shape and size.



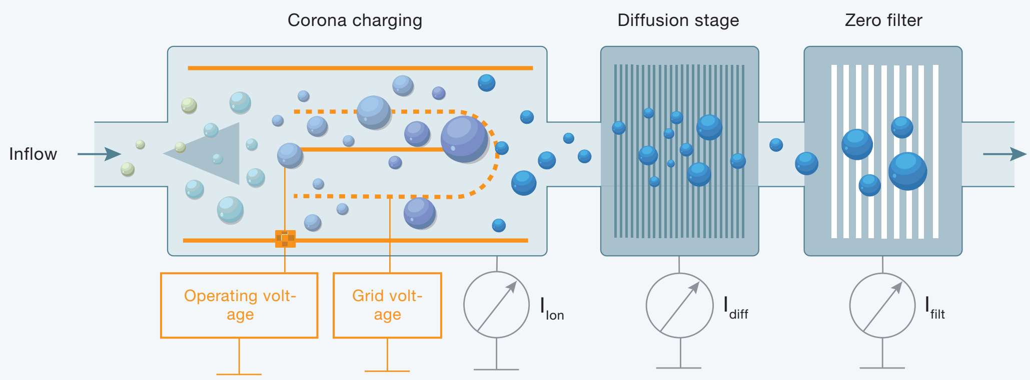
Measurement of the particle size distribution

Measurement methods

The previous section indicated which facets particle measurement can show. Depending on the particle size under investigation, there are measurement methods with varying degrees of precision. In this section, we will describe measurement methods which are used in Testo's measuring instruments.

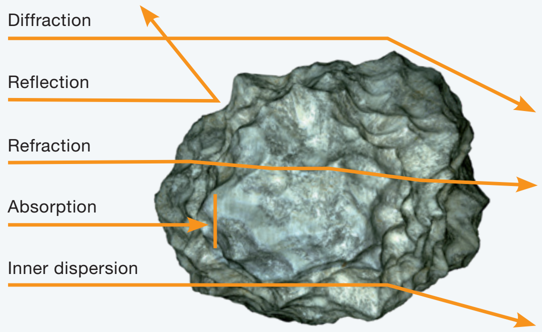
Diffusion charging

Diffusion charging involves using the particles as charge transporters. Browning motion is responsible for the smallest particles moving in the most intense way and thus tending to be deposited in an appropriate filter. Larger particles get past the filters designed for this application without any problem, because they are much more inert and readily follow the air flow. The small particles which are separated in this first stage of filtering give off their charge to the conductive filter, so that the flowing current can be measured and used to calculate the particle number. The sample's larger particles are deposited in the downstream filter stage – the zero filter – and the current strength of the charge flowing out there is also measured.
Sensors with two stages, as used in the patented Testo sensors, are a special feature.
The difference in charge between the two filter stages enables the modal value to be calculated. Modal value is used to refer to the particle size with the highest particle number concentration. In the distribution curve of a monomodal distribution, the modal value is the maximum which the curve reaches for the particle number.
Diffusion chargers can be very suitable for use in the measurement of nanoparticles. There are several manufacturers who use this principle in handheld measuring instruments. At Testo, the principle is applied in the testo DiSCmini and this sensor is also to be found in the testo NanoMet3, a portable emission analyzer for counting nanoparticles in engine exhaust gases.



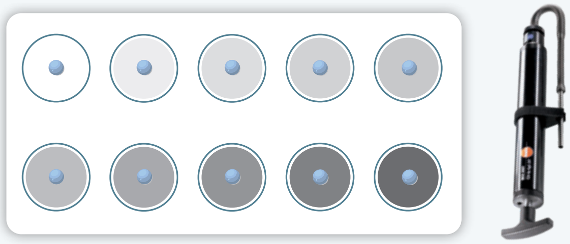
How the diffusion charger works

Optical methods



Light hits a particle

Smoke number comparison scale



Testo hand pump for sampling

For many years now, it has been possible to sample and evaluate combustion flue gases manually. A hand pump is used for this, enabling a defined volume of flue gas to be drawn through an inserted filter sheet with several strokes. The particles found in the flue gas blacken the filter sheet and the degree of blackening can be assessed using a comparison scale. The blackening of the sheet results from the absorption of the incident light, that is the higher the particle concentration of the blackening mark, the more light is absorbed and the darker the filter paper appears.

In spite of exact compliance with the prescribed processes and great care with the sampling itself, manual analysis has the reputation of being difficult to reproduce and dependent on subjective factors. It is therefore a good idea to use automated sampling and sample evaluation with a measuring instrument here. A vacuum pump is used to do this and draws a defined volume of flue gas through a filter sheet. Here too, the particles contained blacken the surface of the filter paper which is illuminated by a calibrated light source. The reflectance of the filter paper is measured before and after the blackening and therefore gives values which enable the filter smoke number (FSN) to be calculated. Both the sampling and the measurement of the amount of reflected light are carried out automatically once the measurement has started and are supported by micro-controllers. This ensures a high level of reproducibility and reduces the falsification of measurement results due to errors to a minimum when taking, analyzing and evaluating the sample.

testo 338 for fast and automatic measurement of the smoke number

Gravimetric measurement

We have already gone into the impactor principle, but it really does make sense to look at this again. For measurements with impactors, you can either weigh the deflector plate after the measurement, or the deflector plate is designed as a sensor which registers the loading with previously electrically charged particles, so that this signal can then be evaluated directly.
The same applies when a quartz oscillator is integrated into the deflector plate. If particles are deposited on the surface of this deflector plate during the measurement, there is a linear change in the oscillation frequency of the quartz as the loading increases. This is picked up directly – evaluation of the signals and calculation of the particle emission in real time thus enables the progression of the measurement to be directly followed, so that reliable measuring values can be determined and the progression of the measurement can also be evaluated. Since its market launch, this sensor has proved its worth in thousands of measurements with the testo 380.

Measuring instruments

Now that some methods for measuring particles have been outlined, in this section we intend to present the instruments which Testo produces for the measurement of particles. In line with Testo's product philosophy, this involves mobile measuring instruments for emission and immission measurement. Their fields of application range from the measurement which chimney sweeps use for the regular checking of solid fuel combustion systems through to the periodic technical inspection (PTI) of the particle emissions on vehicles with the testo NanoMet3.

testo 338 degree of blackening measuring instrument
When assessing the condition of diesel engines and checking them, service engineers know that a sooting engine may be an indicator of defective assemblies or settings. The smoke number, or to put it better the filter smoke number (FSN) enables the evaluation of soot emissions on diesel engines. In contrast to diesel-powered vehicles in road traffic which are fitted with particle filters, machines and vehicles which are in use off the road are still operated without filters.
The testo 338 means every engine technician has a handy instrument available for measuring the soot emissions in the exhaust gas from diesel units and for checking the injection setting. Once the sampling probe has been placed in the exhaust gas flow, the fully automatic measurement can be started at the touch of a button. The testo 338 firstly measures the reflection capacity of the filter paper being used and then pumps a sample out of the gas flow through this paper. Once the required volumes of exhaust gas have been sampled, the feed unit transports the paper through the measuring system and the reflection value is again measured. You can choose to output the measured degree of blackening as a soot concentration in mg/m^3, as a filter smoke number (FSN) or as a Bosch number. The measuring values can be directly read off the display or printed out on a testo fast printer via IrDA. As an option, the testo 338 can also be connected via Bluetooth to a computer which processes the measuring values using the testo easyEmission software. This makes the handy testo 338 the ideal tool and measuring instrument for service engineers and workshops which are commissioned to do work on diesel engines, for example for:

- Engine manufacturers who frequently have to provide proof of the degree of blackening of diesel exhaust gases
- Shipping companies and shipyards, because many port authorities now pay attention to reducing particle exposure due to ships coming into port and those docked there
- Mining companies, because the legal requirements or statutory regulations on diesel machines in opencast and underground mines have to be complied with.
  Smoke number measurements are mandatory in most cases here.
- Tests in the context of the commissioning and maintenance of diesel engines

testo 380 fine particle measuring instrument

It is now fashionable again to use wood for heating. Ultimately, a wood-fired burner not only generates heat, it is also said to provide a much more pleasant ambiance than a radiator. While there is little possibility of proving this subjective feeling, it is on the other hand objectively certain that the emissions of fine particles have also increased with the growing number of systems using solid fuels. This not only involves open fireplaces in the living room, but also large systems using wood chips and pellets.

Since the amendment of the 1st German Federal Immission Control Ordinance (BImSchV), chimney sweeps, heating engineers and stove manufacturers, along with service engineers, have been faced with new challenges. The testo 380 fine particle measurement system, which was specially developed for emission monitoring on small-scale combustion plants, helps them to meet these. The testo 380 comprises two system components: the testo 380 fine particle measuring instrument with fine particle probe and the testo 330-2 LL flue gas analyzer.

The testo 380 is a suitability-tested and innovative complete solution which also measures the values for flue draught, flue gas temperature, oxygen and carbon monoxide in the flue gas, in addition to fine particles, in real time. The heated measuring probe is placed in the flue gas flow and draws off the flue gas for the measurement.

The handpiece of the probe has a diluter which dilutes the flue gas using filtered air and thus also counteracts the undesired condensing of volatile components in the measurement gas.

The measurement gas is fed by the probe via the hose package directly to the pre-heating section for re-tempering, from where it goes directly into the sensor. A nozzle plate equipped with two small drill holes is located above the actual sensor. Here, the measurement gas is rapidly accelerated and hits the deflector plate of the sensor located directly underneath. This rotates, enabling consistent distribution of the particles on the surface. The quartz, which is integrated into the deflector plate, now changes its frequency as the loading of the surface increases. The loading can in turn be calculated from the change and you can choose to have it output as an instantaneous value, a cumulative value or based on standard oxygen.

The testo 380 can be used for:

- Acceptance of newly-installed combustion plants for solid fuels according to points 1 – 8, section 3 of the 1st German Federal Immission Control Ordinance (BImSchV)
- Regular, recurrent checking of installed combustion plants
- Development and testing of combustion plants for solid fuels at manufacturer's sites

testo DiSCmini handheld measuring instrument for nanoparticle counting

Different rules apply in the area of nanoparticles. It is not possible here to work with the inertia of the particles or to analyze them using optical methods. By definition, their size is less than 100 nm. Particles from diesel engines have an average size of approx. 70 nm and particles from modern petrol engines are only approx. 30 nm in size. When mobile instruments are needed, CPCs and diffusion chargers can be used for counting.

The testo DiSCmini works according to the principle of diffusion charging and can process particles with a size of between 10 nm and 700 nm. To do this, the particles are drawn in using the air flow. An impactor at the air inlet ensures that particles with a diameter of over 700 nm are separated. It can easily be cleaned and can be used directly at the measuring point with a Tygon® hose. In the instrument, the particles then meet a high-voltage field in the charging chamber where they can take up an electrical charge according to their size. The ongoing process has already been described in detail in point 2.1.

In addition to the sensor, the handy housing of the testo DiSCmini contains the electronics for control and for analyzing the measurement, the vacuum pump and sensors which measure the volume flow of the measurement gas, the display for showing the instrument status and an SD card for saving the measurement data.

The testo DiSCmini is an immission measuring instrument which not only determines the quantity of emitted particles, but also provides information about the concentration of nanoparticles at the location and time of the measurement.

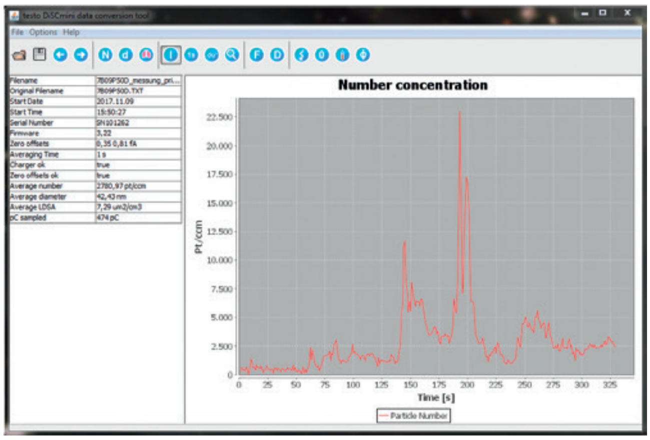
Its fields of application are as follows:

- Workplaces with exposure to particles, e.g. welding and soldering workplaces
- Measurement of the spread of nanoparticles at locations with high emissions, e.g. inner cities and airports
- Scientific research into nanoparticles
- Checking of filters and extraction units for nanoparticles

We recommend the “Book of Abstracts” to all interested parties. Here you will find more than 100 publications on the use of the DiSCmini in science and research. Simply get in touch with us at Testo – we will be happy to send you this interesting book.

The SD card can be removed for analysis of the measurement and the data it contains can be evaluated on any Windows PC using the testo JavaTool software.

It is possible to create diagrams showing the progression of the measurement that can be used in publications and evaluations. Once the data has been acquired, you can also carry out further analyses using Excel.



Evaluation of measurement data using the testo JavaTool software

testo NanoMet3 portable emission measurement system

Since the legal regulations on the emission of particles in combustion flue gases have become stricter and stricter over recent years, a fast and simple assessment of nanoparticle concentration in the context of type approval or periodic technical checks [5] is indispensable. And the evidence of fine particles or the filtering of them is also one of the core themes for the further development of combustion engines. Depending on the efficiency of the engine and the fuels used, the size of these particles is just 20 to 80 nm. The portable testo NanoMet3 particle counter ensures extremely reliable and high-precision determination of both the quantity and the average diameter of solid nanoparticles in accordance with type testing and with reference to the Euro 6c emissions standard.

As a PEMS-PN (Portable Emission Measuring System, Particle Number), the testo NanoMet3 is absolutely cutting edge. As it is not only easy to use, but also portable, it enables the investigation of both the emission of particles under RDE (Real Driving Emission) conditions in vehicles on the road and in combustion engines in the context of NRMM (Non Road Machinery Measuring) in terms of the particles they emit.

Once it is switched on, it can be operated using a button. The measurement either runs fully automatically or can be controlled via the AK protocol in conjunction with additional analysis devices. The testo NanoMet3 not only has an operational DiSC sensor, it also has integrated, fully PMP-compliant measurement gas preparation. The volatile components of the sample are evaporated in the evaporation tube, the subsequent dilution of the measurement gas in the rotating disk diluter cools the sample down and the dilution prevents the re-condensation of the evaporated components. With this kind of treatment, only the solid soot particles in the flue gas get through to the analysis in the DiSC sensor. In terms of its function and effect, the sensor corresponds to the one described in point 2.1. The PMP-compliant flue gas preparation which is integrated into the testo NanoMet3, its unlimited portability, robustness and ease of use, along with its interfaces with other systems, make it a complete particle measurement laboratory for the following applications:

- Tests in engine research and development
- Particle measurement on rolling-road test benches
- Particle measurement under real conditions on test drives (RDE)
- Recurrent checking of the particle concentration in the context of periodic technical inspections (PTI)

[5] https://media.testo.com/media/e8/41/47f415644643/testo-NanoMet3-Example-Application-Mexiko-EN.pdf