

Device for Measuring Solid Particle Number Concentration from Combustion Sources

TSI Nanoparticle Emission Tester Model 3795

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New TSI Instrument nanoparticle emissions tester is a tool for measuring the total solid number concentration of particulate matter from combustion sources, like the exhaust from a diesel engine.

Motivation

- + Concentrations of particulate matter in modern engine exhaust is low due to the use of Diesel Particulate Filters (DPFs)
- + DPFs can fail in the field
- + Swiss Regulation 941.242
 - Mandates in-use testing of non-road mobile machinery DPFs
- + Problem:
 - Detecting DPF failure is challenging for field mass/opacity based systems
- + Solution:
 - Measurement of *solid* particle number concentration



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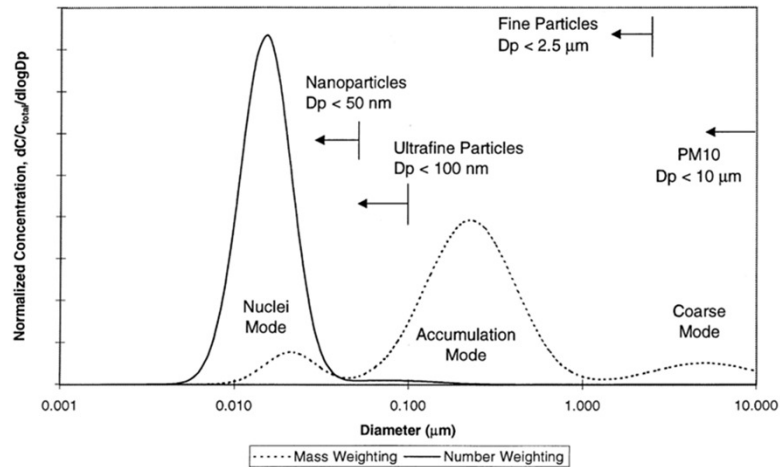
Exhaust from modern engines with aftertreatment systems such as Diesel Particulate Filters (DPFs) or gasoline particulate filters (GPFs) is extremely clean, and when the aftertreatment system is working properly the exhaust can have lower particle mass and number concentrations than the ambient air.

However; if a DPF or GPF fails, due to separation, cracking, or melting, or due to a malfunctioning regeneration system, it can allow very high levels of particle matter to pass through unfiltered. It is possible for the DPF to still capture the majority of the mass, while still permitting a high number of particles to pass through the DPF.

Current field methods of measuring particle concentrations in engine exhaust are mass or opacity based and are challenged by the very low concentrations of PM downstream of a DPF. While laboratory instruments exist to measure the mass to very low concentrations, there is a need for a tool capable of measuring the low concentrations of particulate downstream of a DPF in the field.

Rather than using mass or opacity, by measuring particle number, the detection limit is pushed to a much lower concentration, making it much easier to delineate between functioning and failed DPFs.

Typical engine exhaust particle size distribution



Kittelson, Journal of Aerosol Science, 1998

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Engine exhaust is mainly composed of semi-volatile material and solid soot.

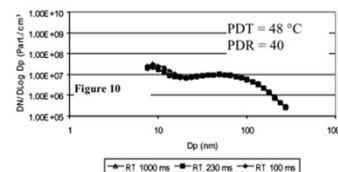
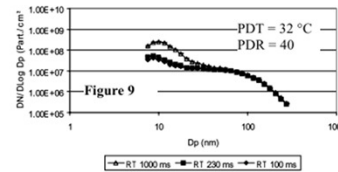
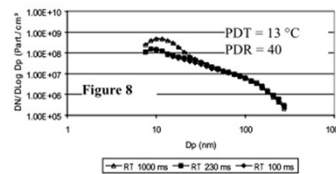
As shown in the idealized trimodal lognormal size distribution of diesel aerosol from Kittelson's 1998 review paper, the bulk of the mass is contained within the accumulation mode, while the majority of the number concentration is contained within the nucleation mode.

The bulk of the accumulation mode is solid, non-volatile material, while the nucleation mode is mainly volatile material

The size and concentration of volatile materials is heavily dependent on dilution conditions->

Why solid particle number concentration?

- + Condensation of semi-volatile exhaust components can greatly affect particle size and number concentrations
- + Dependent on dilution conditions
 - Dilution ratio
 - Concentrations of semi-volatiles
 - Temperature
 - Residence time
- + Solid particles are not easily affected by ambient dilution conditions



Abdul-Khalek et al., SAE International, 1999

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As exhaust cools, the volatile components (unburned or partially burned fuel, lube oil) and sulfates can homogeneously condense creating volatile particles, as well as condense onto existing solid particles or sulfur or ash nuclei, increasing their size.

The level at which the condensation of volatile material affects concentration and size measurements is heavily dependent on dilution conditions.

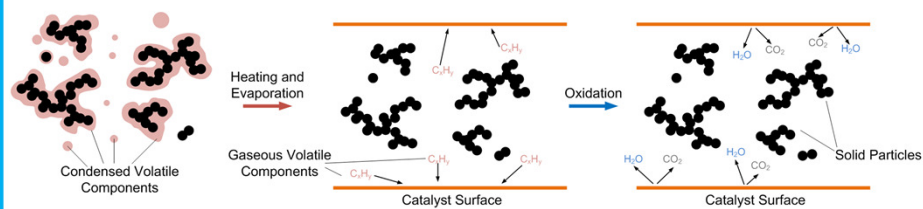
Exhaust diluted in a cooler environment will lead to much higher rates of condensation and result in a more drastic increase in particle concentration than exhaust diluted in a hot environment.

To compare apples to apples, either the dilution conditions must be very carefully controlled, or the volatile particles must be removed, as the solid particles are not easily affected by dilution.

The Nanoparticle emissions tester removes volatile material prior to measurement with a CPC:

Methods of removing volatile particulate matter

- + Volatile particle removal (VPR) tube
 - Evaporates volatile material
 - Uses secondary dilution to prevent re-condensation
- + Thermal denuder
 - Evaporates volatile material
 - Volatiles adsorb into activated carbon
- + Catalytic stripper
 - Evaporates volatile material
 - Volatiles are oxidized using a catalyst to prevent them from re-condensing



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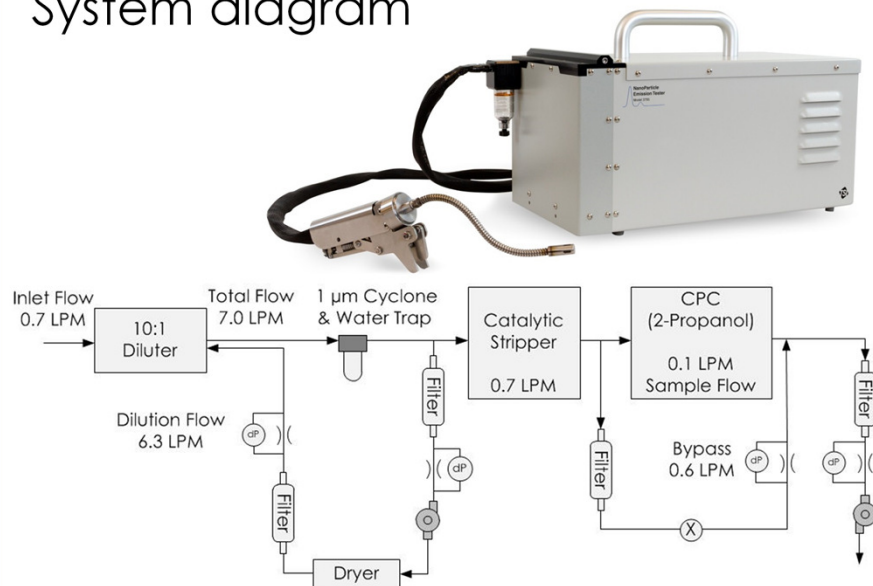
Three common methods of removing particulate matter are:

The volatile particle remover (like in PMP) which is a heated tube that evaporates the volatile particulate matter. A secondary dilution step is used to avoid the recondensation of volatile particles and reduce thermophoretic losses.

The thermal denuder which evaporates the volatile material. The gaseous volatile material is then adsorbed into activated carbon.

And the catalytic stripper, used in the 3795 nanoparticle emissions tester, which evaporates the material, and then oxidizes it to prevent it from recondensing.

System diagram



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TSI 3795 Nanoparticle Emission tester

Stainless steel sample probe clamps onto the exhaust pipe. The probe has 10:1 (nominal) dilution.

The dilution air is filtered, dried, exhaust that is processed within the instrument itself using the sample conditioning loop.

The diluted sample then passes through a 1 micron cyclone/water trap to remove large particles and any water droplets.

A catalytic stripper, heated to 350 °C removes greater than 99% of the volatile material.

The remaining solid particles are counted by a isopropyl based CPC with rechargeable wick so there is no liquid reservoir. The wick lasts 4-hours before needing to be recharged.

The instrument is controlled by a software package that is designed for a tablet PC, for ease of use in the field. The software has two modes, a general purpose research mode and a official certification test mode that is

General Measurement Mode



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The 3795 NPET system is controlled by software optimized for a windows 8 tablet but will run on windows 7.

Connecting to the instrument via ethernet, the software contains two operation modes.

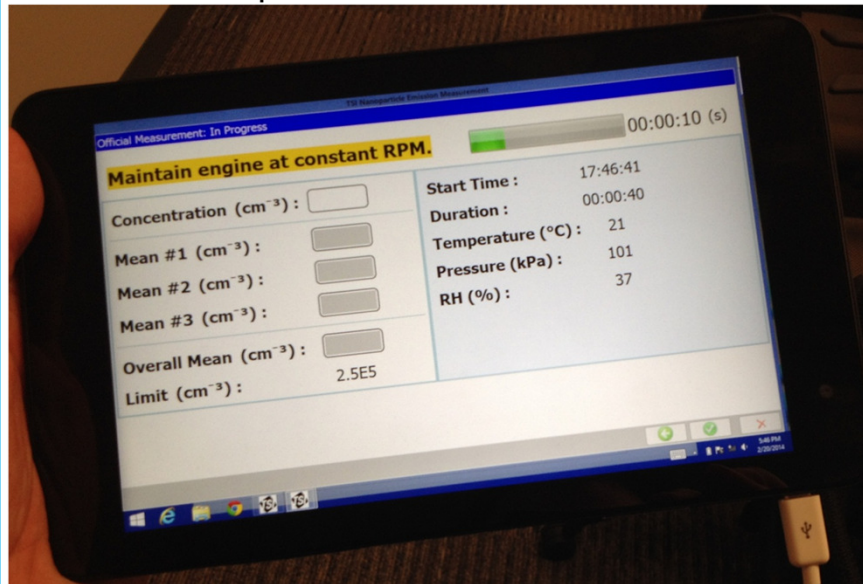
The general measurement mode features

- 1 hz data collection
- A live strip chart as well as live updating cumulative statistics.

The second mode is the official operation mode

- Which is compliant with swiss regulation 941.242
- Completes an official measurement in under 1 minute
- Stores the official reports in a locked PDF format.

Official Operation Mode



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Technical Specifications Overview

- + Detection Efficiency:
 - <30% at 23 nm
 - >65% at 41 nm
 - >90% at 80 nm
 - 100% at 200 nm
- + Concentration Range
 - 1000 to 5×10^6 cm⁻³
- + Response Time
 - $T_{10-90} = 4 \pm 0.5$ s
 - $T_{0-90} = 8 \pm 0.5$ s
- + Volatile Particle Removal
 - >99% for 30 nm tetracontane (C₄₀H₈₂)
- + Environmental Operating Conditions
 - Temperature : -10°C to 40°C
 - Pressure : 70 to 106 kPa
 - Sample Inlet temperature: <300 °C

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The instrument is designed to be portable and used in the field, with a wide ambient temperature and elevation range

Due to the use of a built in dilution system, the instrument has a very broad range from 200 to 5×10^6 particles/cc, the use of the dilution system also results in a T 10-90 of 4 seconds and a T 0 to 90 of 8 seconds.

The volatile particle removal efficiency is greater than 99% as shown on the next slide

The detection efficiency specifications are slightly different than a traditional CPC. They are a tightened subset of the Swiss standard's requirement for detection efficiency, but basically the d50 will fall somewhere in the 23 to 41 nm range, where the detection efficiencies are specified to be below 30% and greater than 41%, respectively. This is also shown in more detail on the following slides.

Summary



- + Device for measuring total solid particle number concentration
- + Designed for field/portable use
- + Performance evaluated
 - Heavy duty diesel engines in the field
 - Light duty diesel engine on dynamometer
 - Comparison with miniCAST generated soot aerosol
- + Good agreement with established technology
 - Not PMP compliant