New Catalytic Stripper System for the Measurement of Solid Particle Mass, Number, and Size Emissions from Internal Combustion Engines

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Particulate matter (PM) emitted from combustion sources, particularly diesel engines, is typically composed of volatile and solid material. The solid material ("soot") consists mainly of carbon and a small amount of inorganic ash. The volatile material consists of unburned and partially burned fuel and lubricating oil, and sulfur compounds. Dry soot particles are formed in the combustion chamber of an engine while most of the volatile material enters the particle phase from the gas phase as the exhaust cools. Hence, particulate matter is a combined measure of solid and volatile particles. It is important to be able to distinguish between the two components because the mechanism of their formation and control are different. Such information can also be useful for researchers investigating the effect of particulate emissions on human health.

A catalytic stripper system referred to in this work as the solid particle measurement system (SPMS), Patent Pending, was designed to allow for the measurement of real time solid particle mass, size, and number in the size range from 10 nm to 500 nm. The SPMS consists of a heated mini oxidation catalyst and a micro-dilution system to cool the heated sample by dilution and prevent particle thermophoretic deposition downstream of the oxidation catalyst. The SPMS is equipped with two 47 mm filter holders for the measurement of solid particle mass and total (volatile plus solid) particle mass. Similarly, the SPMS is also equipped with sample ports for total and solid particle size and number measurements.

The SPMS is a stand-alone system on a moving laboratory cart. All that is needed is an electric power outlet. Vacuum and compressed air sources are available on-board. The SPMS is also equipped with a Labview data acquisition system and a laptop computer for data processing and data analysis.

The SPMS was characterized with sodium chloride, ammonium sulfate, and engine oil particles. The SPMS removed more than 99 percent of engine oil without generating sulfuric acid particles. The SPMS had better than 99 percent penetration of sodium chloride solid particles.

The SPMS was applied to measure particle number and size distributions from a 1998 DDC Series 60 heavy-duty on-highway diesel engine operating at high and low engine load. The total particle number-weighted size distribution was bimodal in nature with a nuclei mode at about 20 nm and an accumulation mode at about 50 nm. The solid particle number-weighted size distribution in the accumulation mode was similar to that of total, suggesting that the majority of accumulation mode particles for this engine are solid in nature. For the nuclei mode, a significant reduction in particle number was obtained downstream of the SPMS, suggesting that the majority of particles in the nuclei mode are volatile and were removed by the catalyst used in the SPMS.

The SPMS also revealed, however, that under most engine operating conditions the solid fraction, the ratio of solid to total particle number in the sub 20 nm diameter range increased and exceeded 100 percent for particles between 9nm and 11 nm in diameter. By the definition of the solid fraction, it is not surprising to have a solid fraction over 100 percent. The following example explains how that can be possible. Suppose 50 percent of one hundred 10 nm solid particles present in the exhaust grew by the absorption of volatile material to a size above 10 nm. For the total size distribution, one would measure 50 particles with size 10 nm and 50 particles above 10 nm. If one applies the SPMS, one would measure a 100 solid particles for 10 nm particles. The solid fraction for 10 nm particles will then be 200 percent. This new findings suggest the presence of a solid core in the sub 20 nm particle size range that may go down to below 9 nm, the lower detection limit of the instrument used on this program. The nature of this solid core may be solid carbon or possibly metallic ash from the engine lubricating oil. Such information is extremely important to the health authorities trying to understand the effect of particles on human health.

The application of the SPMS in future work is expected to generate significant information as to the composition and characteristics of particulate emissions from combustion sources. Coupled with a Nano-SMPS or similar devices that can measure particle size and number down to 3 nm, the use of the SPMS is expected to provide significant information as to the generation and growth of even the smallest of particles.

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Acknowledgments

• This work was funded by SwRI Committee for Internal Research and Development.

Note

- The new catalytic stripper system will be referred to as the solid particle measurement system (SPMS) throughout this presentation

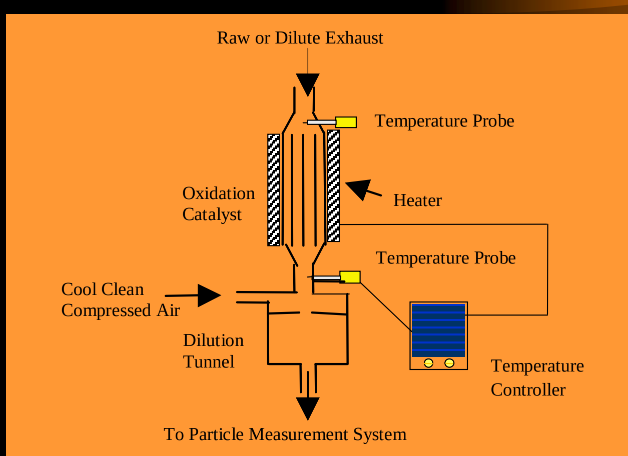
Outline

- What is the SPMS?
- Characterization with Laboratory Aerosol
- Application on A Heavy-Duty Diesel Engine
- Conclusions

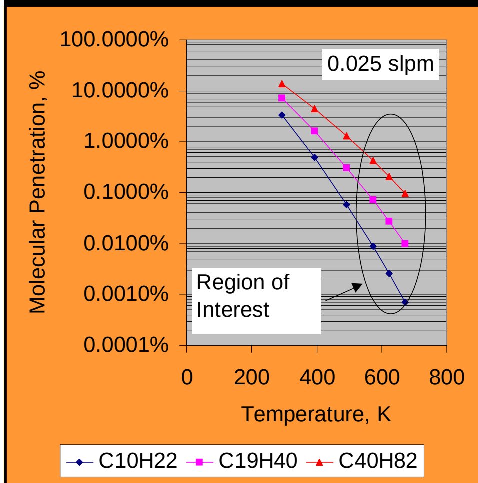
SPMS Development Objectives

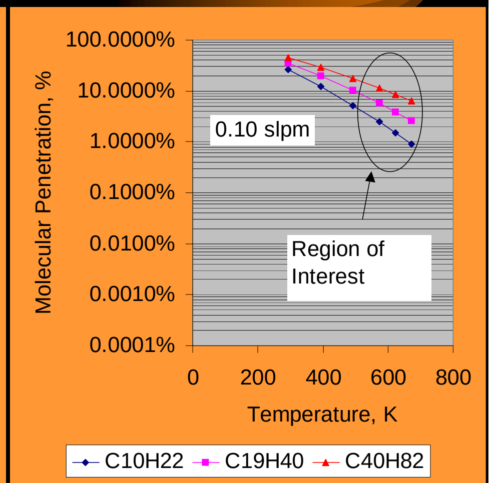
- To Develop a Stand-Alone Laboratory Instrument that Facilitates the Measurement of Solid Exhaust Particle Mass (Filter and Non-Filter based), Number, Size, and Other Physical PM Characteristics Using Different Real Time Instruments
- To Minimize Solid Particle Losses and Achieve Near a 100 Percent Penetration of Solid Particles
- To Maximize the Removal of Volatile to Near 100 percent
- To Prevent the Potential Formation of Sulfuric Acid Particles
- To be Capable of Measuring Total PM (Solid and Volatile) So Volatile PM can be Determined
- To be Used Either with Diluted or Undiluted Exhaust Stream

SPMS Principle of Operation

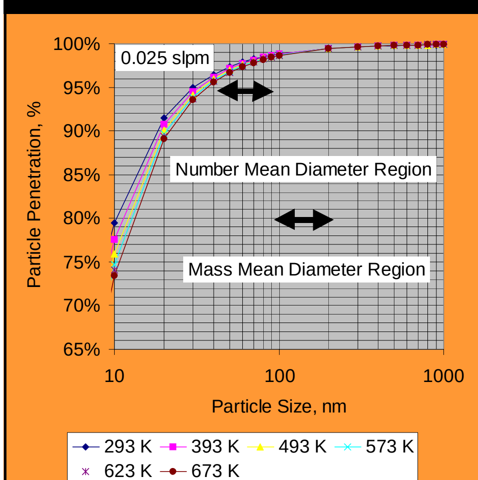


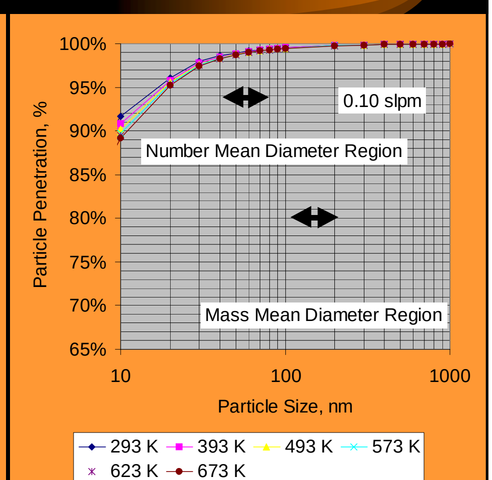
Example of Gas Diffusion and Flow Optimization In Catalyst Square Channel



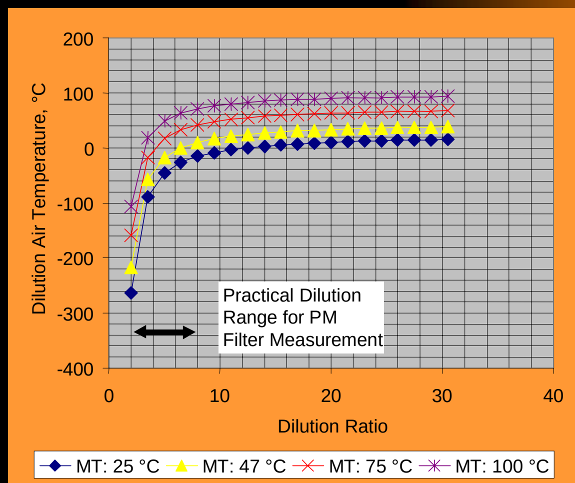


Example of Particle Penetration and Flow Optimization In Catalyst Square Channel



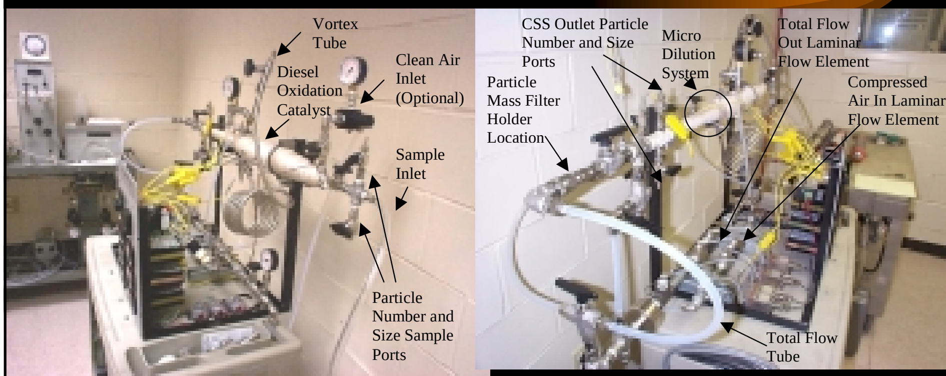


Example of Dilution Ratio and Temperature Requirement at the Exit of Catalyst at Temperature of 300 ^{o}C

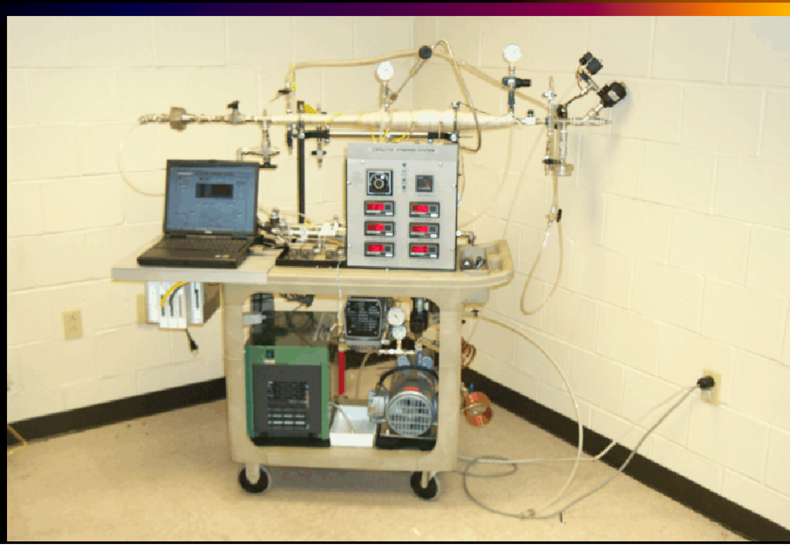


Cutting The Appropriate Size Catalyst from The Stock Catalyst

Partial View of the SPMS



Stand-Alone SPMS

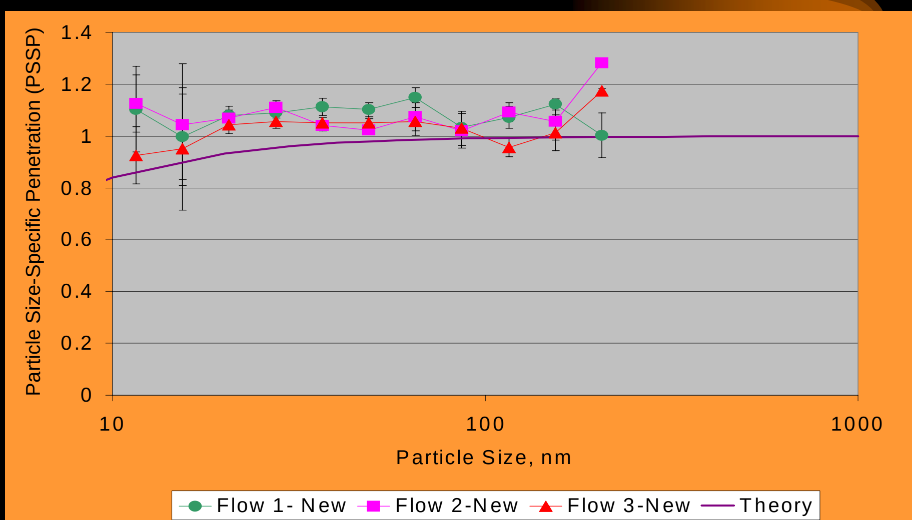


SPMS Characterization with Laboratory Aerosol (Nominal Flow and Dilution Ratio)

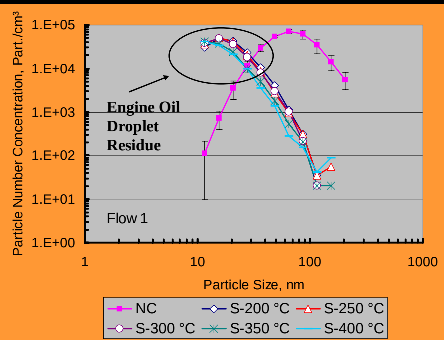
Unheated CSS

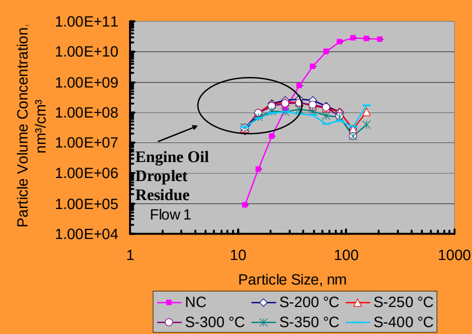
Flow Conditions	Total Flow (slpm)	Air Flow (slpm)	Sample Flow (slpm)	Dilution Ratio
1	65.2	49.4	15.8	4.12
2	73.9	49.2	24.7	2.99
3	80.4	49.2	30.2	2.57
Heated CSS (300 °C)				
1	70.7	49.7	21.0	3.36
2	64.3	49.2	15.1	4.25
3	60.0	50.0	10.0	6.00

SPMS Performance with NaCl Particles at 300 °C

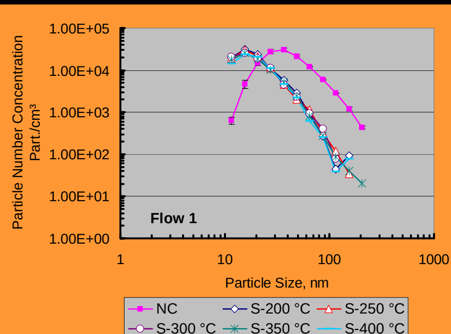


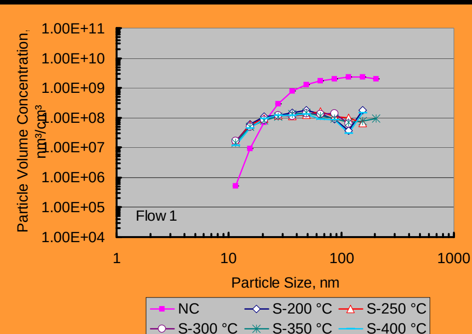
SPMS Performance With Engine Oil Droplets



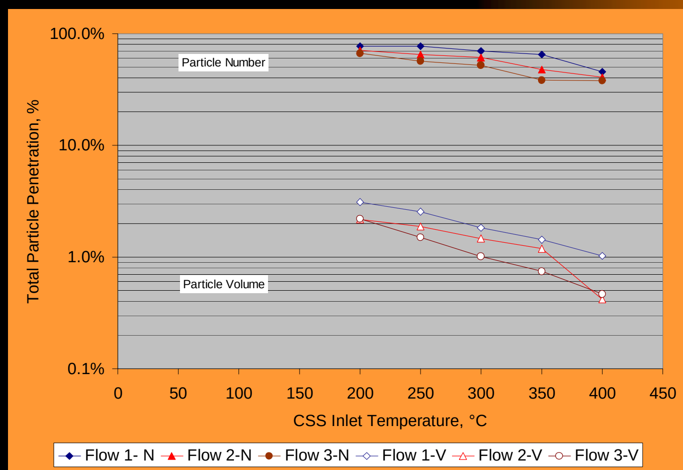


SPMS Performance with Ammonium Sulfate Particles





Particle Penetration for Engine Oil Droplets Based on Number and Volume

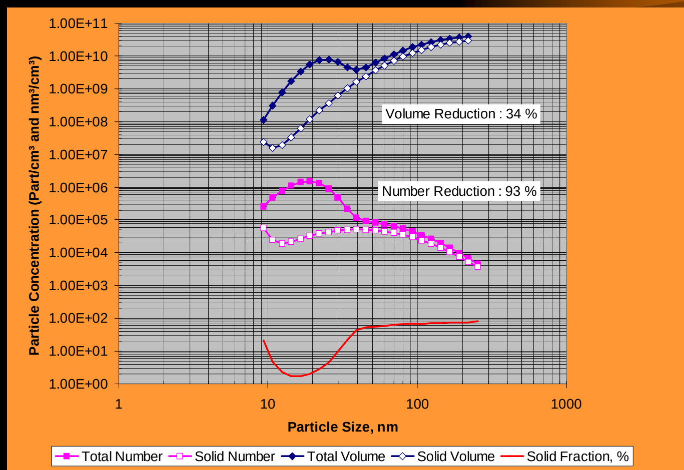


Engine Test Matrix

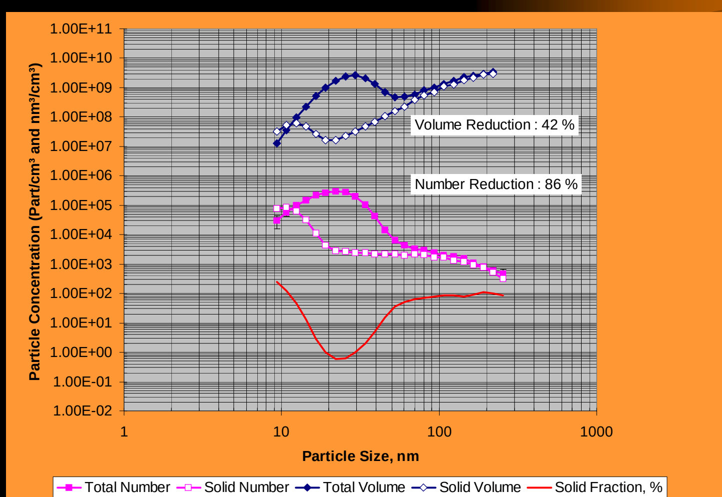
Mode	Speed, rpm	Load, % of Load at Rated Speed	Number of Repeats
1	1800	65	6
2	900	25	6
3	1800	35	6
4	600	0	6

1998 DDC Series 60 Heavy-Duty Diesel Engine

Total and Solid Particle Size Distributions Using SPMS (Heavy-Duty Diesel Engine Operating at High Load, Rated Speed, Mode 1)



Total and Solid Particle Size Distributions Using SPMS (Heavy-Duty Diesel Engine Operating Near Low Idle, Mode 4)



Summary

- A Stand-Alone SPMS was developed for Solid and Total Particle Mass, Number, and Size.
- Solid Particle Losses were at minimum level and no correction is need in the size range from 10 nm to 300 nm.
- The SPMS removed more than 99 percent of oil droplets
- No apparent formation of sulfuric acid particles
- Engine Emissions Data revealed that some of the volatile droplets contain a solid core. It is possible to attribute such core to Ash derived from the lube oil.
- This instrument Can be a very useful for Assessing Solid ,Volatile, and Total Particles in Real Time.
- More Detail Description and Analysis of the SPMS will be available in future publications

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