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Characteristics of Diesel Particulate Matter Loading on PTFE Membrane Filters

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We investigated Diesel particulate matter (DPM) loading on PTFE filters using pressure drop measurements and scanning electron microscopy (SEM), and compared our results with theoretical models (Endo et al., 1998, Kim et al., 2009). The study was motivated by the soot loading problem in Diesel particle filters (DPF), which is one of the most popular methods for Diesel exhaust treatment. In our experiments, the loading was on flat filter discs and the prevailing conditions resulted in the filtration process occurring almost entirely in the dust cake regime. Our experimental conditions were different from those in DPF loading, however, we were able to use dust cake loading models combined with measured parameters to gain more insight into the filtration process and the properties of the emitted particulate matter, specifically, primary particle size and to some extent, inferred composition. In addition, information on the cake structure and porosity was achieved. The following describes the methods and results in detail.

DPM was generated using a two cylinder (0.5 L), indirect injection, 4 kW Cummins Diesel engine coupled with an electric motor generator to apply load. The engine complies with the US Tier 2 stationary engine DPM emission standards of 0.8 g/kW-hr. Exhaust was sampled using a single stage dilution system that uses an ejector dilutor to mix the dilution air and exhaust streams at a ratio of 20:1. Diluted exhaust (10 – 20 mg/m3) was used to load PTFE membrane filters that were analyzed gravimetrically to determine the mass gained.

Mass determined gravimetrically includes mass due to carbonaceous agglomerates and adsorbed organic carbon species (Kittelson, 1998). To quantify this effect a catalytic stripper (CS) was used to remove the organic carbon fraction by passing dilute Diesel exhaust over an oxidation catalyst heated to 300°C. Filter samples were taken before and after the CS. After loading, we measured the thickness of the dust cake using a specialized microscopic optical technique. Thickness, loaded mass, and particle density were used to calculate the porosity of the soot layer. The primary particle size of the deposited particles was measured from SEM images (Figure 1). Porosity combined with face velocity and primary particle size were used to calculate the pressure drop using the model by Endo et al. 1998 and Kim et al. (2009).

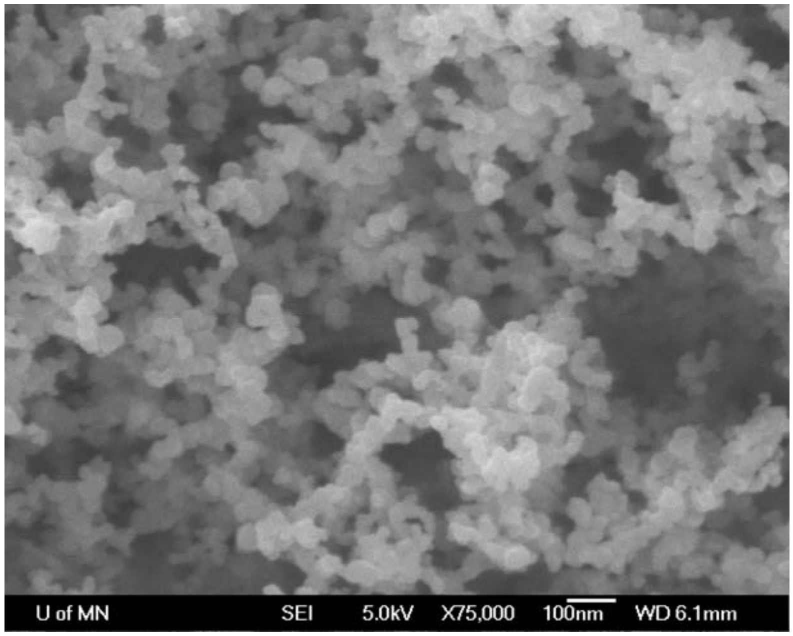

Figure 1. SEM image of the cake formed by the Diesel particles on the PTFE filter.

Our results show that Diesel particulate concentration and mean particle size increase with increasing engine load. Use of the catalytic stripper results in very small changes in the particle size distribution, a less porous dust cake, and a higher pressure drop for a given mass loading. The theoretical model for the pressure drop gives rise to satisfactory fitting of the experimental data (Figure 2).

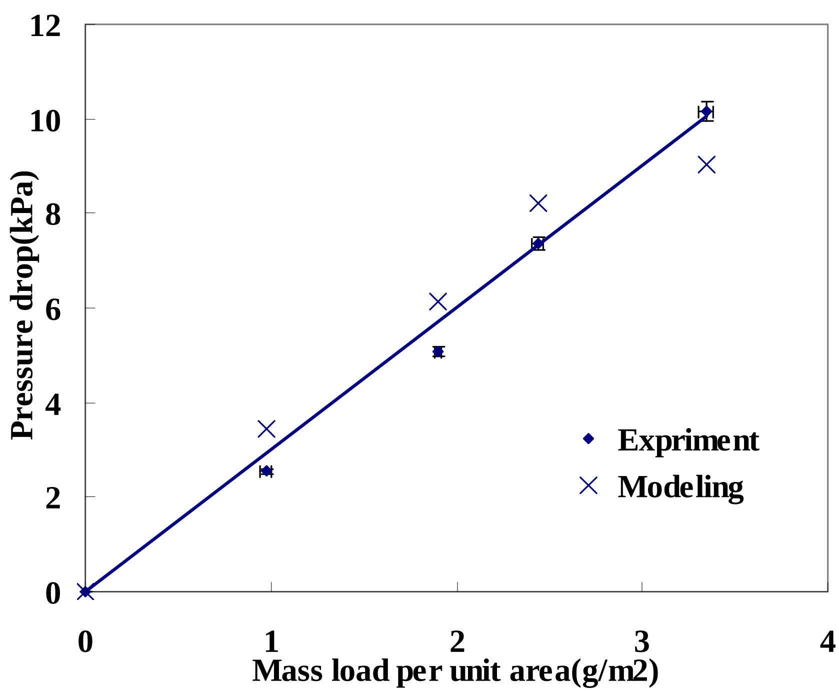

Figure 2. Comparison between the experimental and modelling results for the pressure drop as a function of loading mass.

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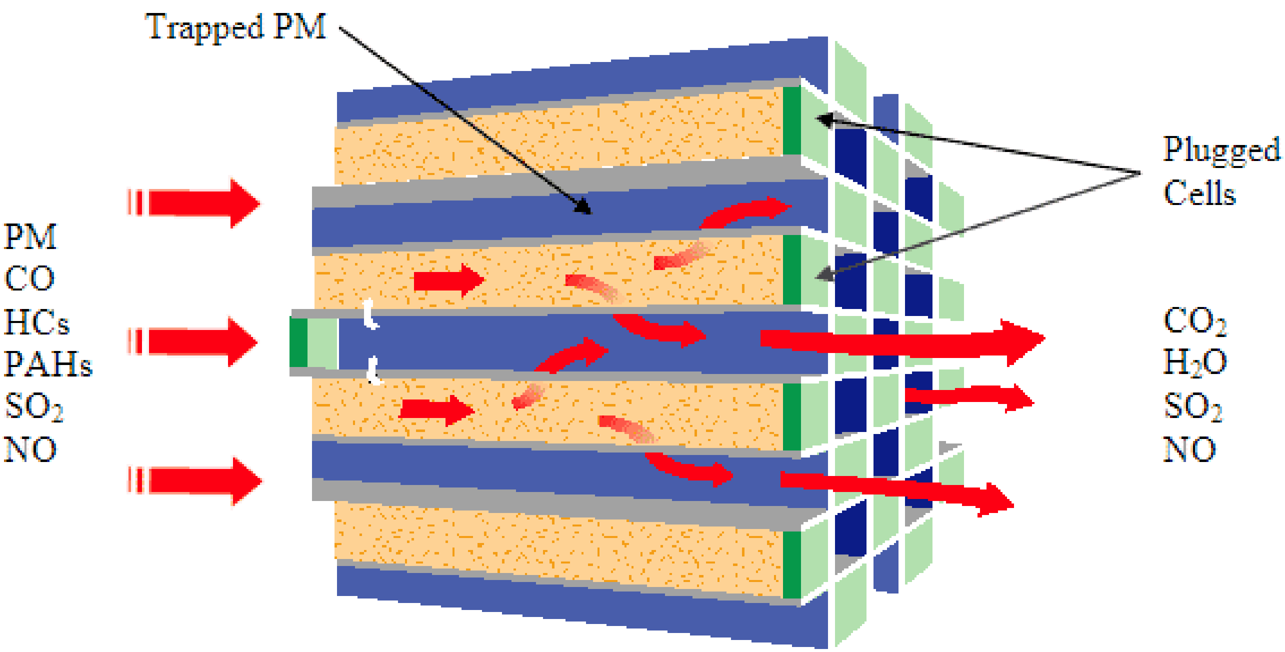
Background



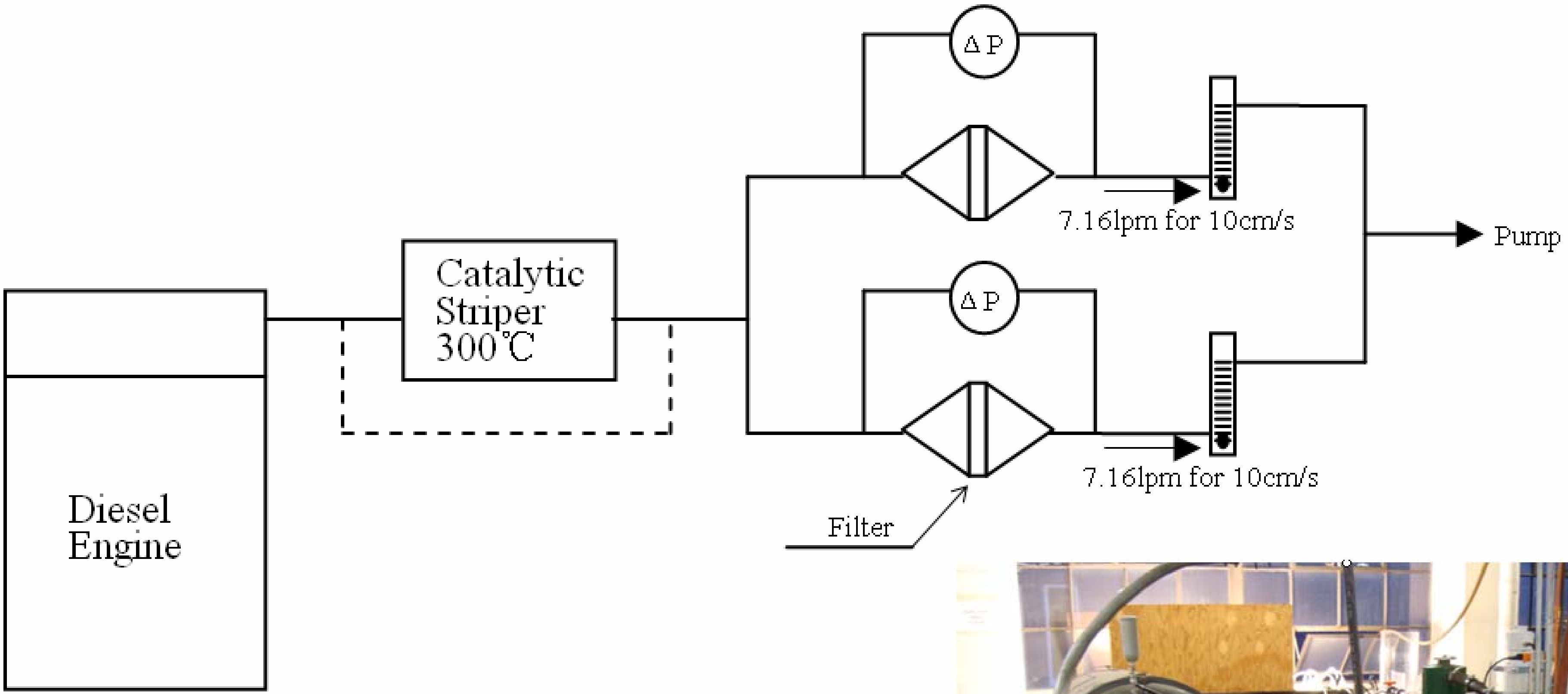
DPF Regeneration, on-time and on-demand schemes

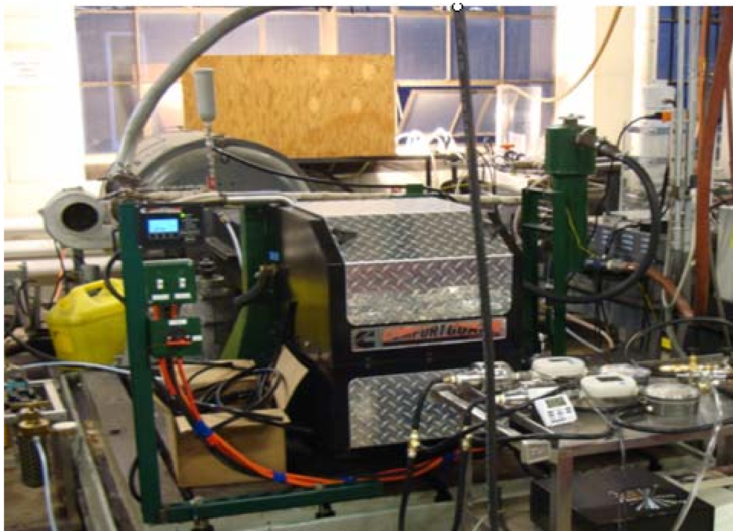
- the loading process of DPM on PTFE membrane filters and modeled the pressure drop as a function of the loading mass.

Outline

1. Experimental setup
2. Particle and dust cake characterization
3. Loading curves and effects of the face velocity, catalytic stripper, and engine load
4. Modeling results
5. Conclusion

1. Experimental setup





Exhaust conditions

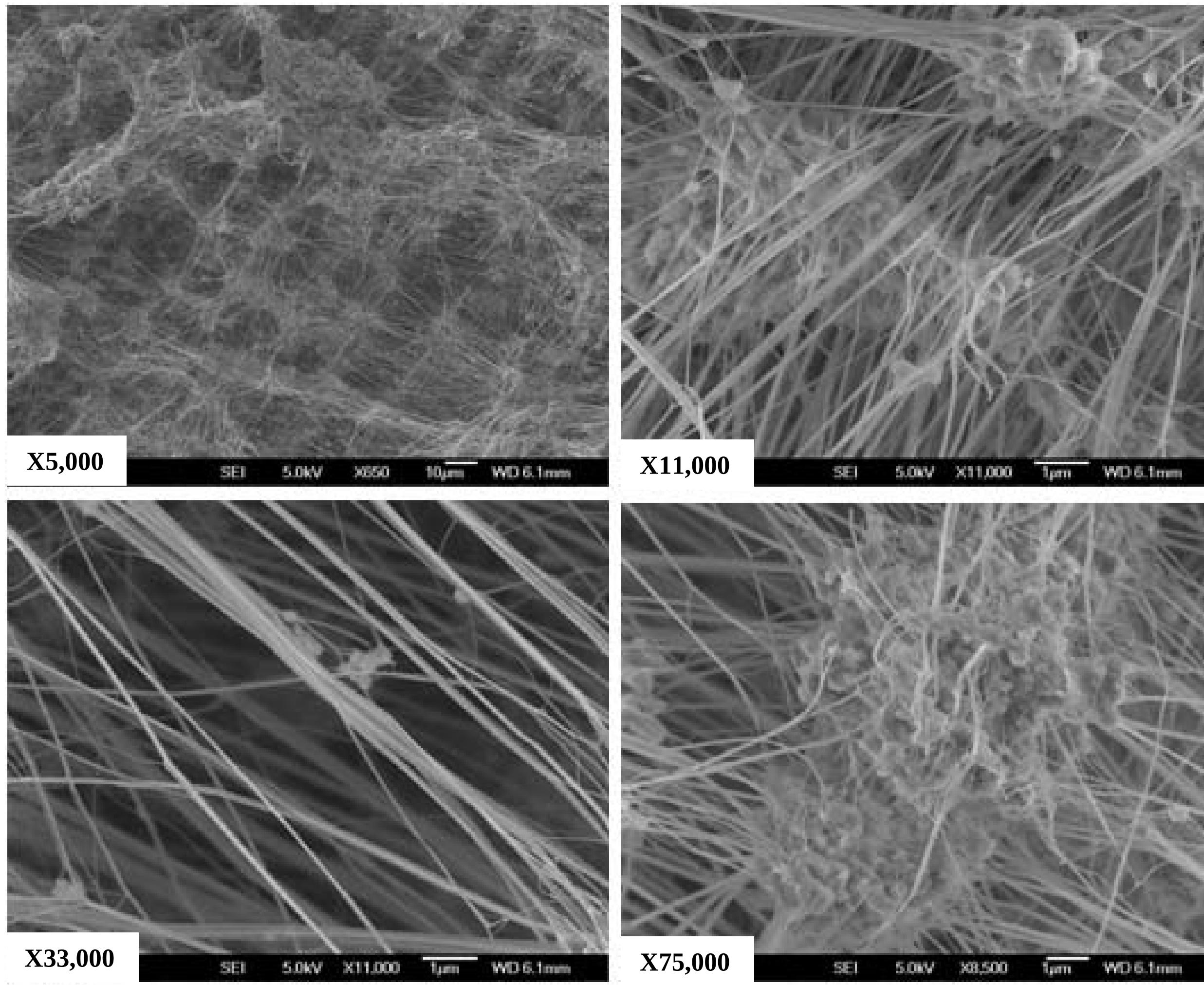
- DPM was generated using a two-cylinder (0.5 L), indirect injection, 4 kW Cummins diesel engine coupled with an electric motor generator to apply load.
- The exhaust was sampled using a single-stage dilution system that used an ejector dilutor to mix the dilution air and exhaust stream at a ratio of 20:1.
- The catalytic stripper was used to remove semi-volatile organic carbon.
- The diluted exhaust stream (10 – 20 mg/m^3) was used to load PTFE membrane filters which were then analyzed gravimetrically to determine the mass gained.

Test matrix

Face velocity (cm/s)	Engine load	Catalytic stripper	Sampling was stopped at different values of the pressure drop (inH_2O)
5	75%	No	10, 20, 30, 40, 50
10	75%	No	10, 20, 30, 40, 50
20	75%	No	10, 20, 30, 40, 50
10	75%	Yes	10, 20, 30, 40, 50
10	37.5%	No	10, 20, 30, 40, 50
10	37.5%	Yes	10, 20, 30, 40, 50

PTFE membrane filter

- The PTFE (*Polytetrafluoroethylene*) membrane disc filters were used for loading.

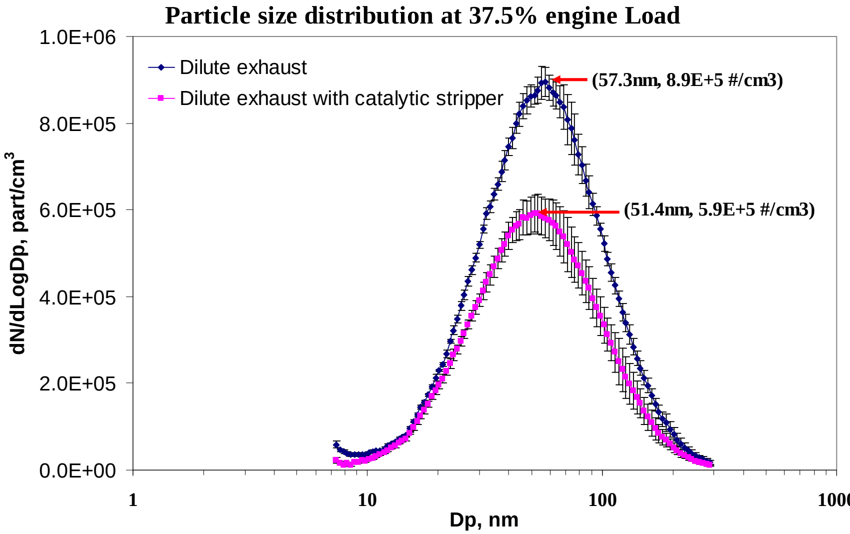


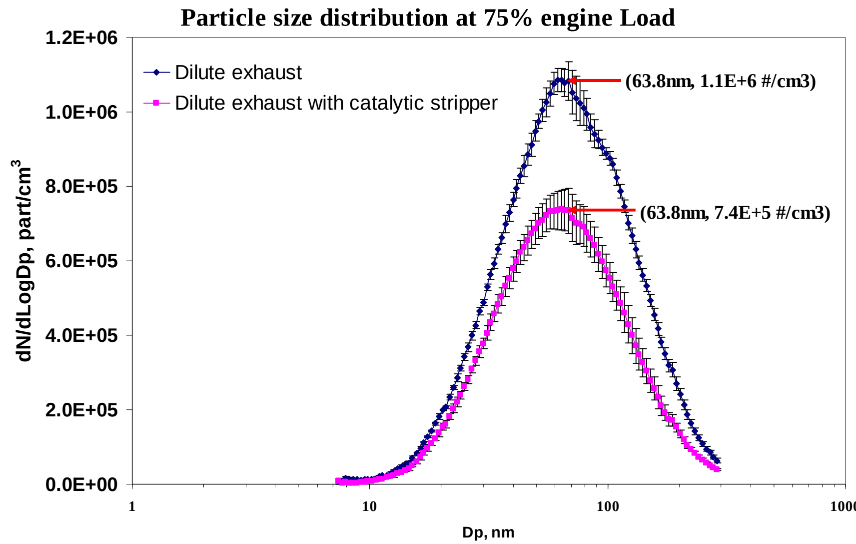
PTFE Membrane filter

2. Particle and cake characteristics

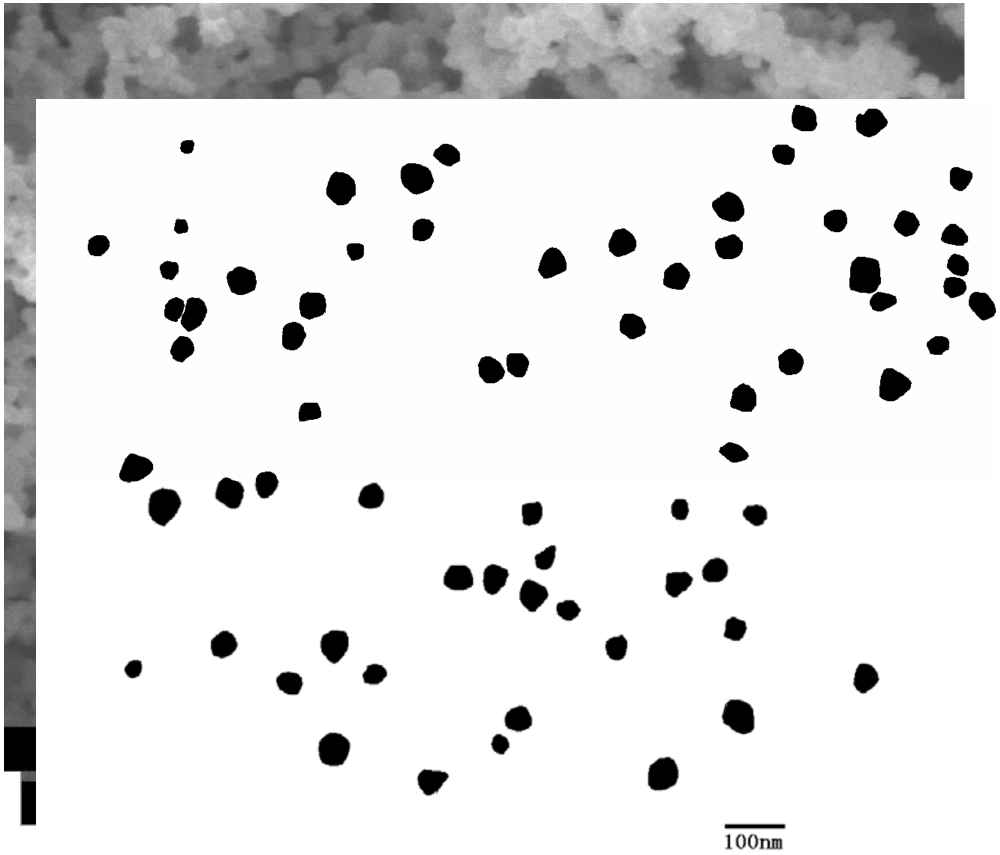
- For 37.5% engine load, exhaust temperature is 170℃
- For 75% engine load, exhaust temperature is 240℃
- Particle concentration at high engine load is greater than at low engine load.

Conditions: Engine load	Conditions: Catalytic stripper	Peak of the size distribution
37.5%	No	57.3 nm
37.5%	Yes	51.4 nm
75%	No	63.8 nm
75%	Yes	63.8 nm





SEM of the particle cake

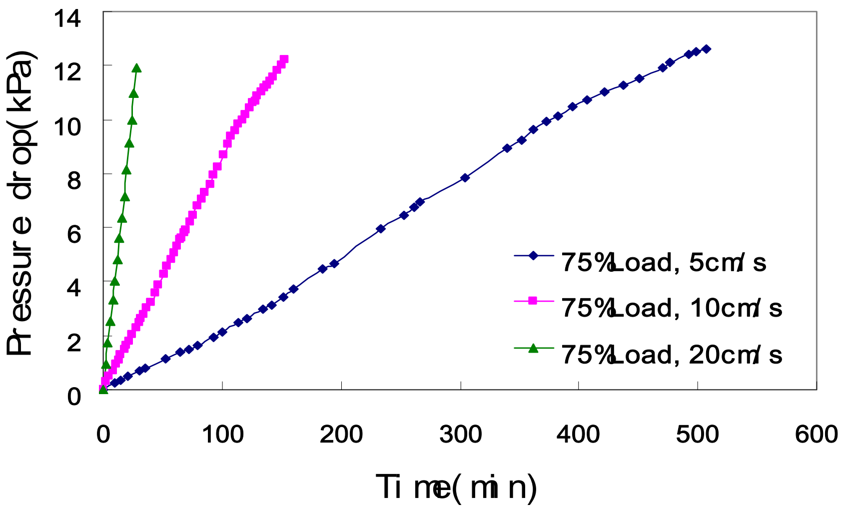


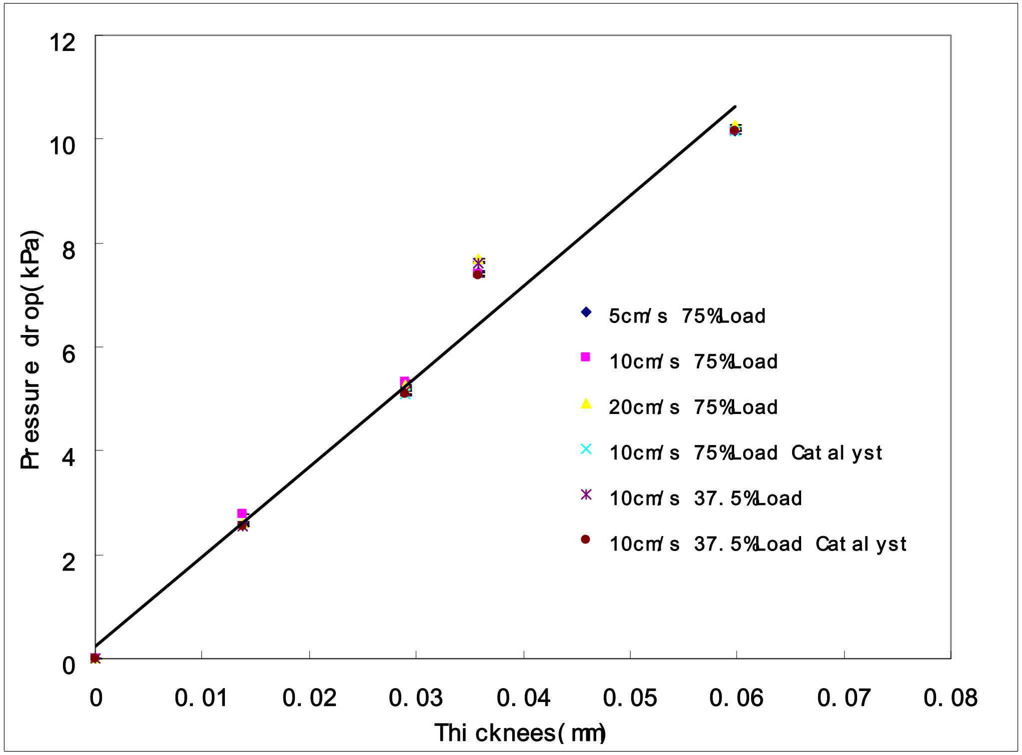
The cake looks like formed by primary particles. Individual diesel particle agglomerates cannot be distinguished.

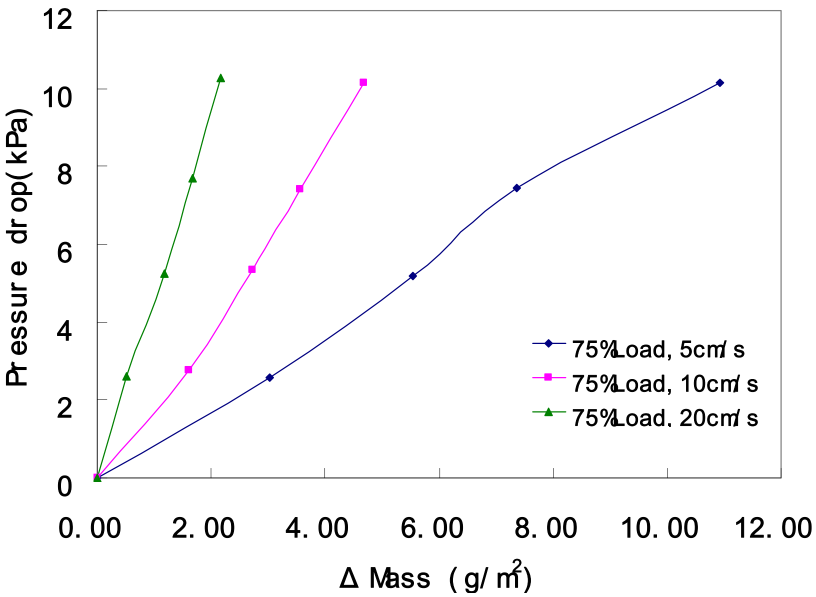
Conditions		Mean primary particle size
Engine load	Catalytic stripper	
37.5%	No	40.1 nm
37.5%	Yes	37.0 nm
75%	No	44.9 nm
75%	Yes	44.3 nm

3. Loading curves

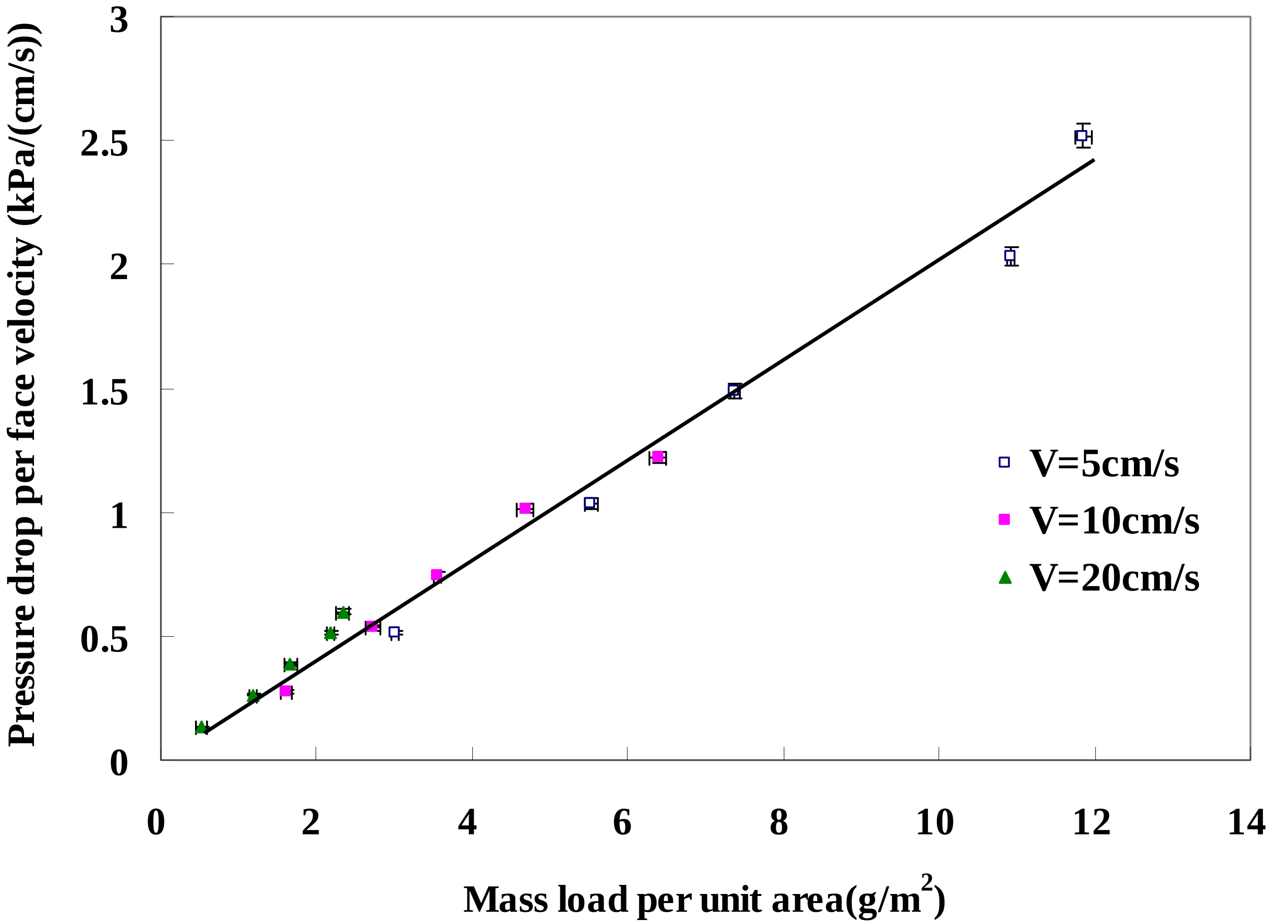
- Increase of the pressure drop is approximately linear with time, mass load and cake thickness
- Pressure drop increases faster at higher filtration velocity







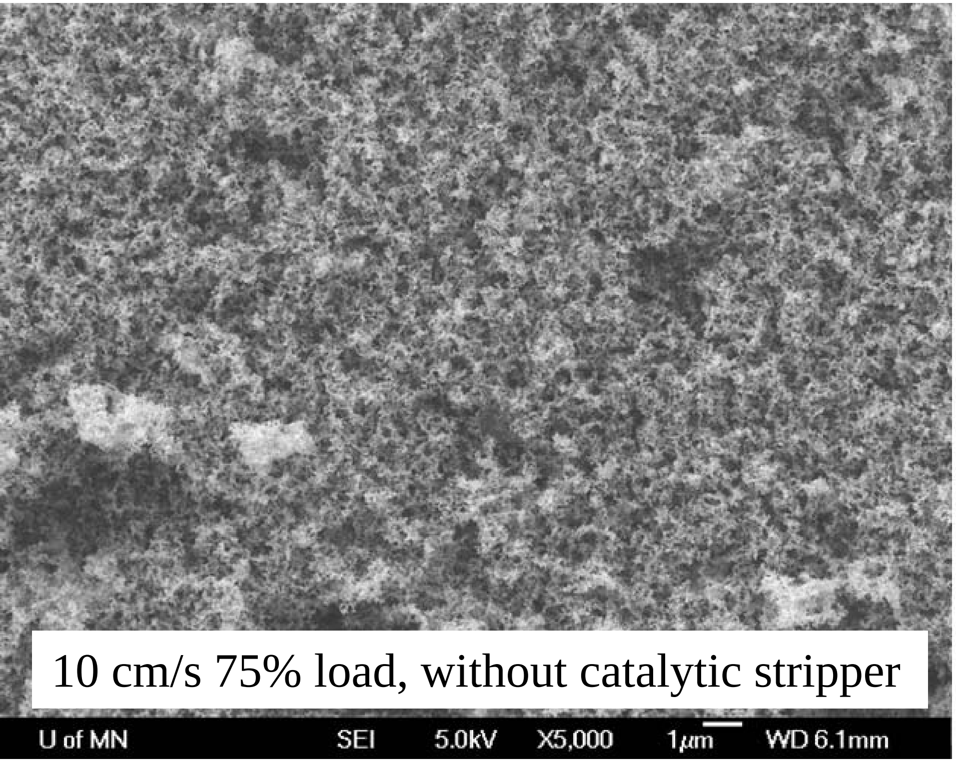
Pressure drop normalized by face vel



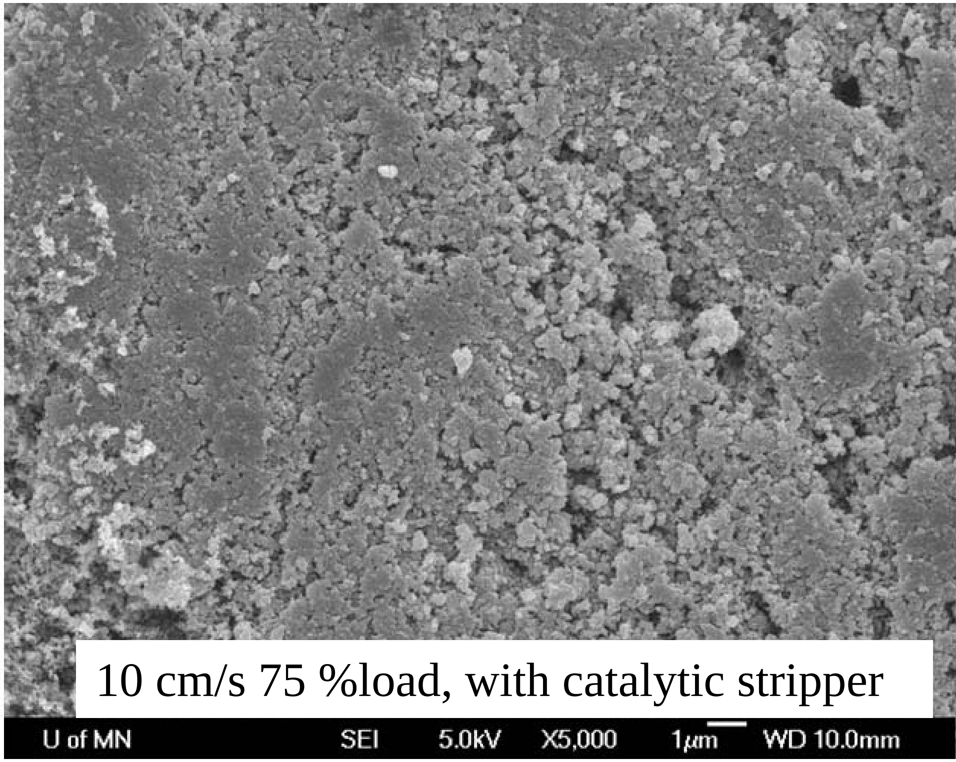
- All the experimental points fall on the same linear curve when the pressure drop is normalized by the face velocity.

Effects of the catalytic stripper

- Without catalytic stripper: carbon particles and organic material deposited on filter sample together.
- With catalytic stripper : catalytic stripper removed the organic materials in the particles, make the cake compact.



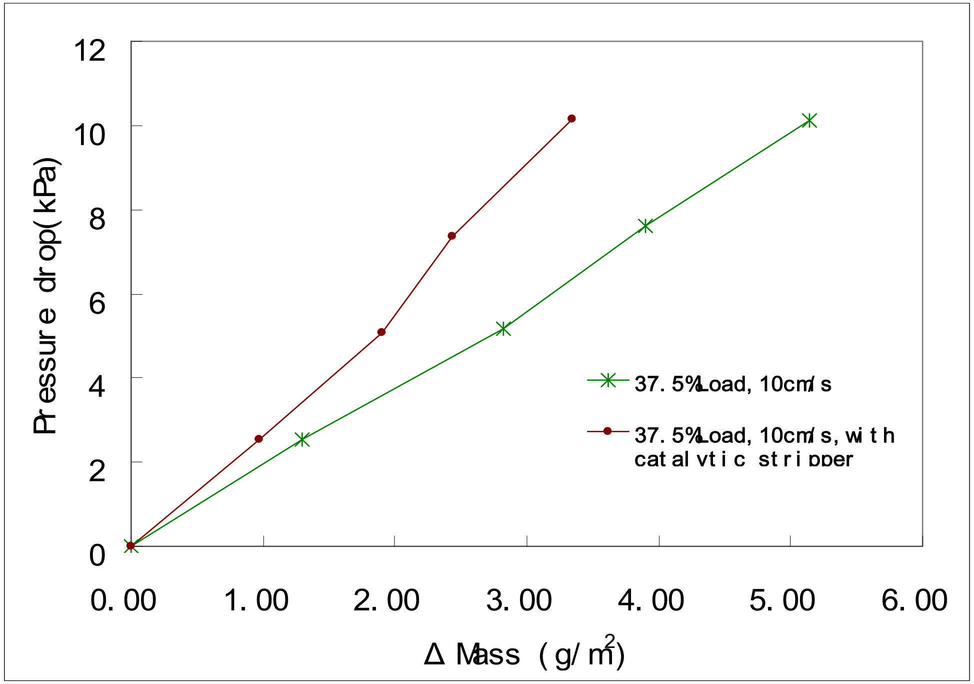
10 cm/s 75% load, without catalytic stripper

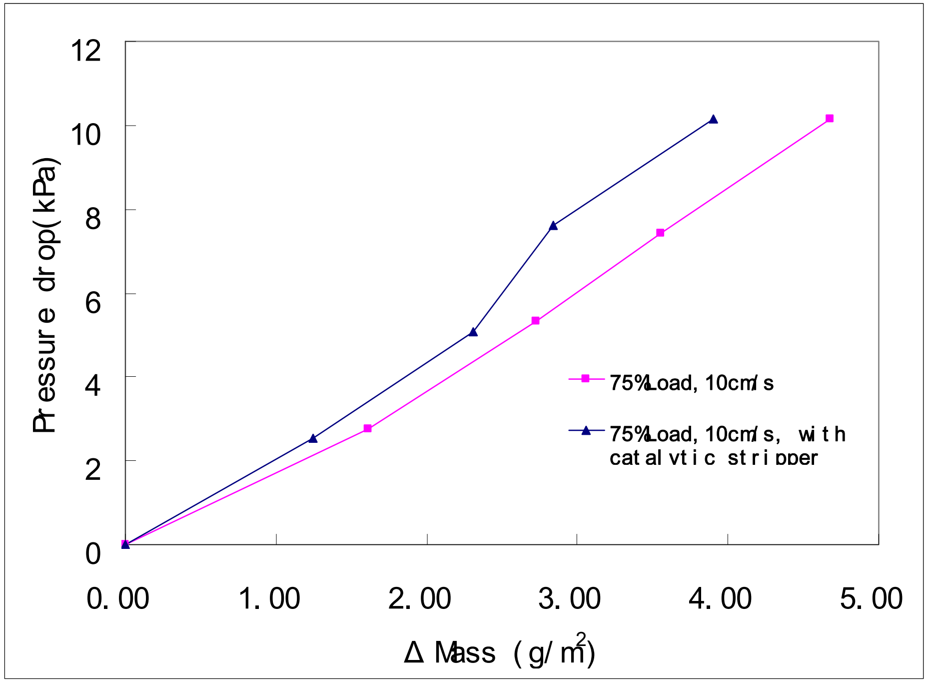


10 cm/s 75 %load, with catalytic stripper

Pressure drop: with and without CS

- Compact cake and smaller primary particle size associated with the catalytic stripper led to a higher pressure drop than when the catalytic stripper is not used.

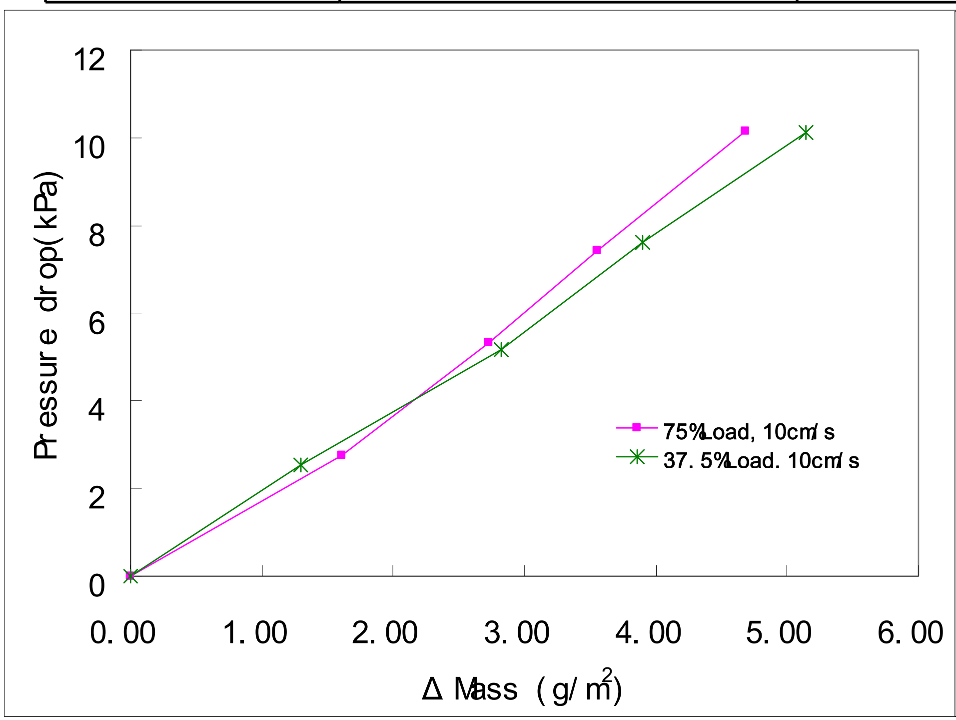


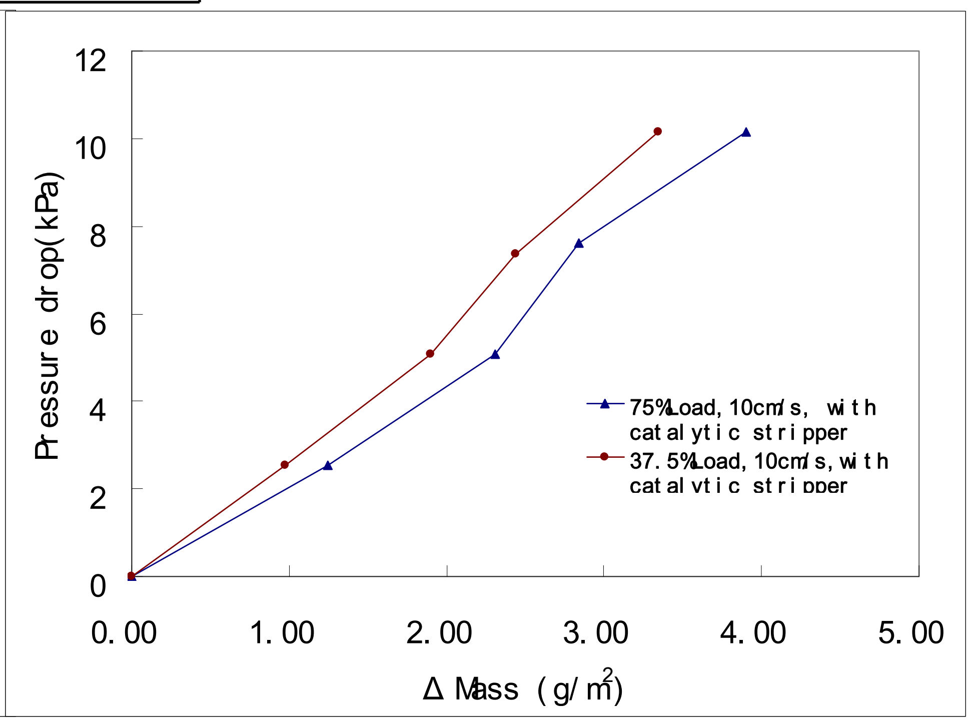


Effects of the engine load

Conditions		Mean primary particle size
Engine load	Catalytic stripper	
37.5%	No	40.1 nm
37.5%	Yes	37.0 nm
75%	No	44.9 nm
75%	Yes	44.3 nm

The engine load had limited effects on the primary particle size and the loading curve plotted against the loading mass.





4. Model analysis

- Following theoretical consideration of a particle-packed bed, the pressure drop can be modeled as[1,2]:

$$\Delta P_c = 18\mu U_f H \frac{(1-\varepsilon)\upsilon(\varepsilon)}{\varepsilon^2} \frac{\kappa}{d_{vg}^2 \exp(4\ln^2\sigma_g)}$$

$$\varepsilon = 1 - \frac{M_c/\rho}{HA_f} \qquad \upsilon(\varepsilon) = 10\frac{1-\varepsilon}{\varepsilon}$$

•μ : gas viscosity
•U_f : face velocity
•d_{vg} : geometric mean of primary particles
•σ_g : geometric standard deviation
•κ: dynamic shape factor

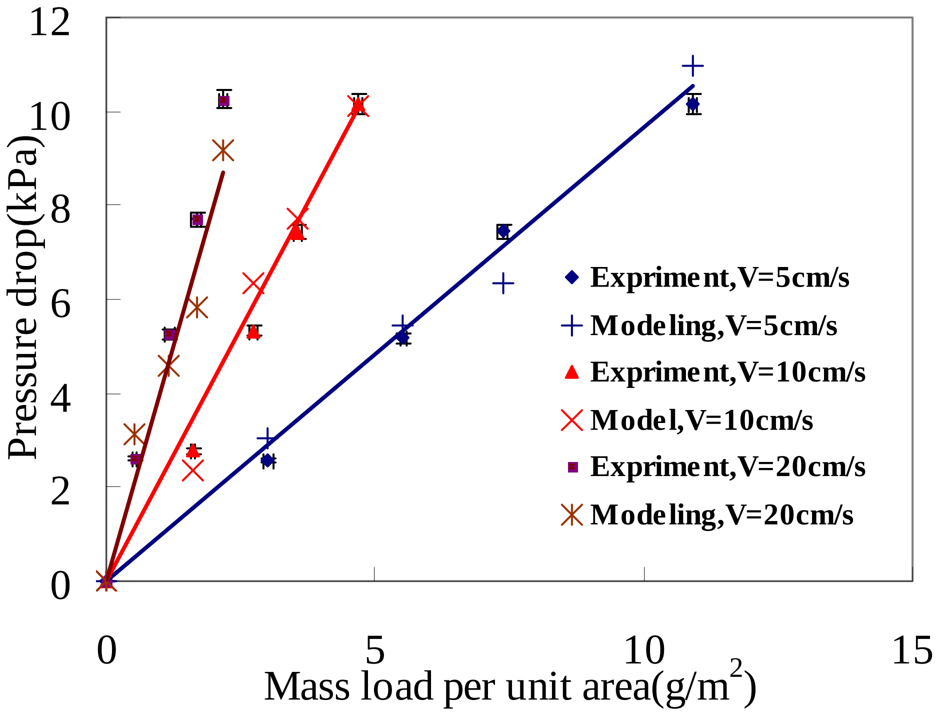
•ε: porosity of particle cake
•M_c : Load mass of particle
•ρ : real density of particle
•H : thickness of cake on filter, Measured by microscope
•A_f: area of filter

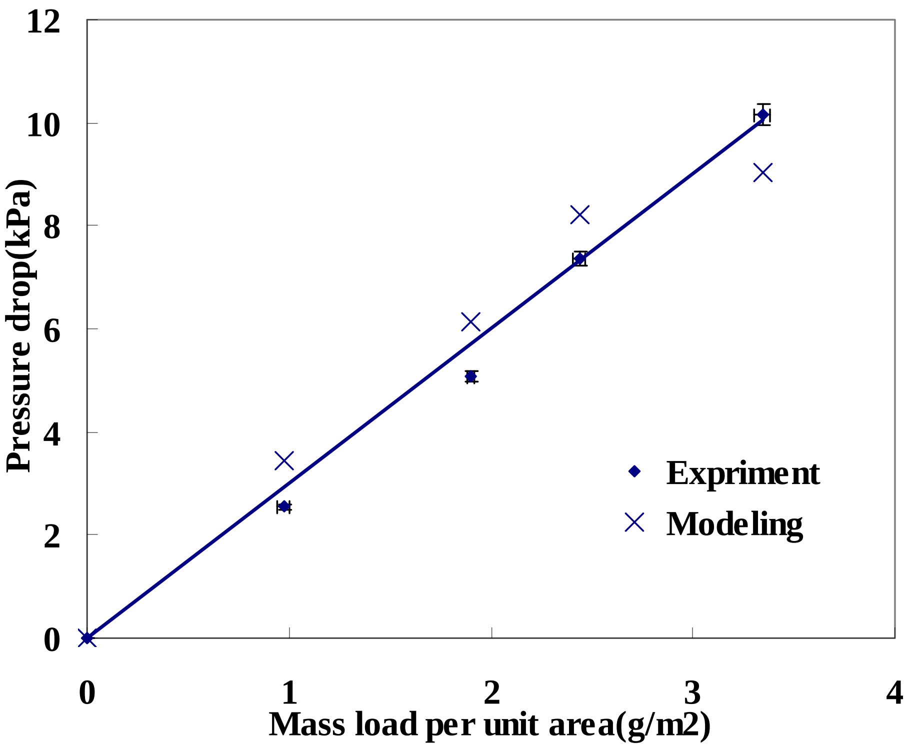
1. Endo, Chen & Pui (1998), Powder Technology.
2. Kim, Wang, Emery, Shin, Mullholand & Pui, (2009), Aerosol Sci & Tech

Modeling results

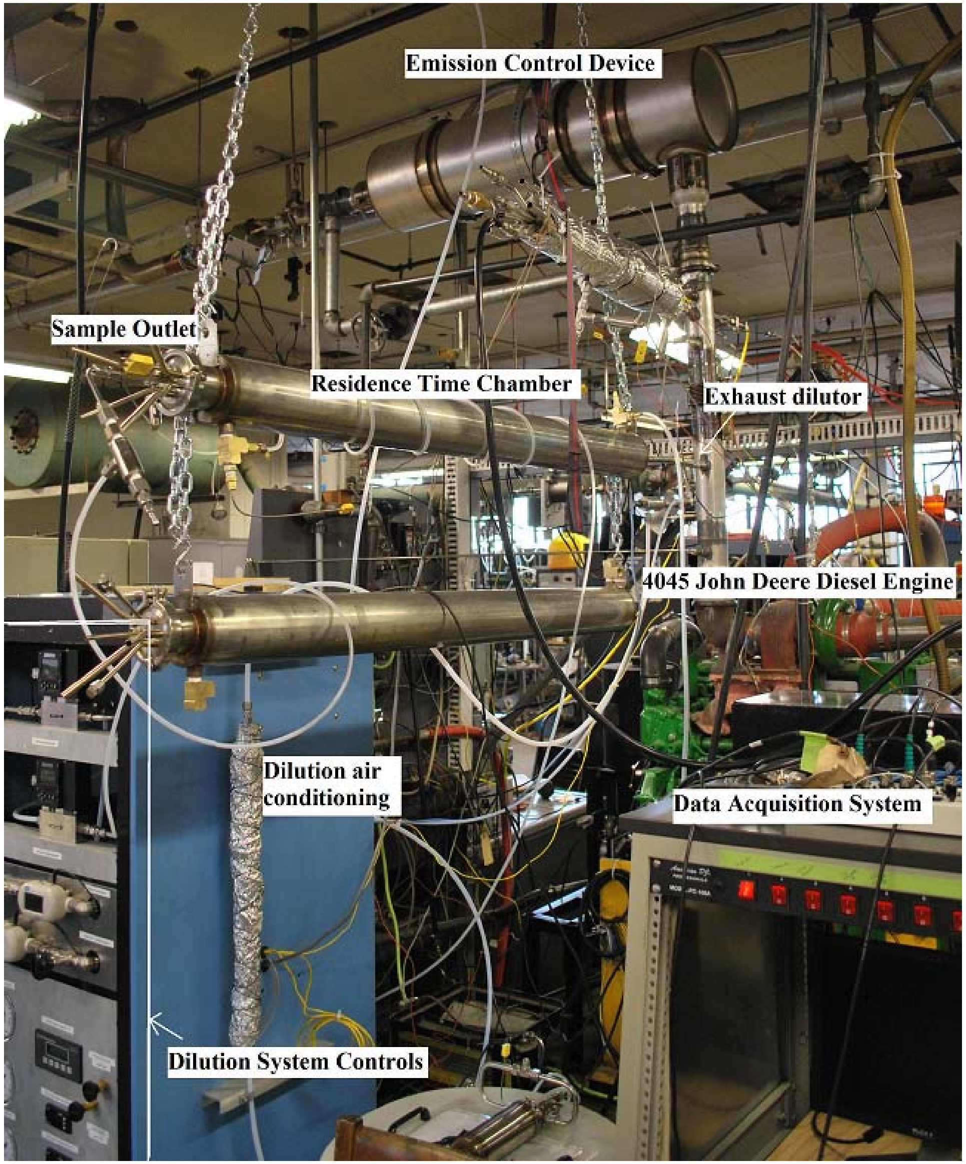
Parameters	75% load no catalytic striper	37.5% load with catalytic striper
ρ(g/cm3)	1.8	1.8
Af (m2)	0.0012	0.0012
μ (Pa.s)	1.8×10^{-5}	1.8×10^{-5}
dvg (nm)	44.9	37.0
κ	1, sphere	1, sphere

- The model agrees reasonably with experiment data
- Pressure drop is approximately linear at the research limit





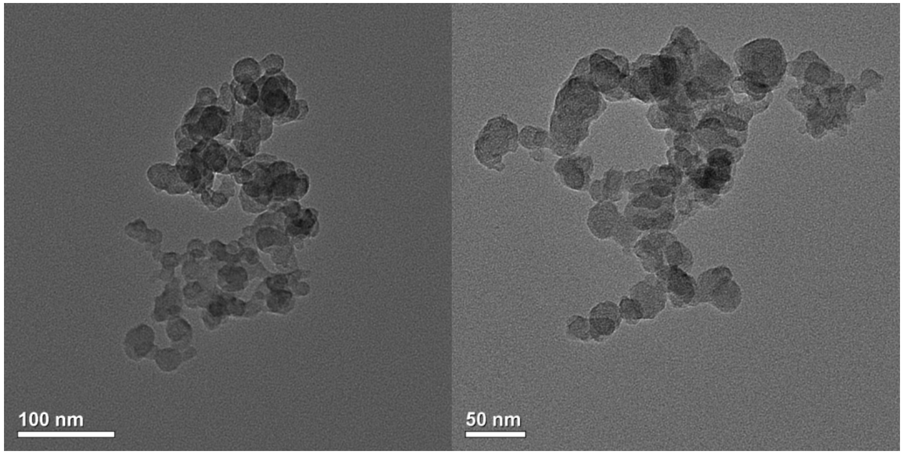
Online measurement of diesel particles



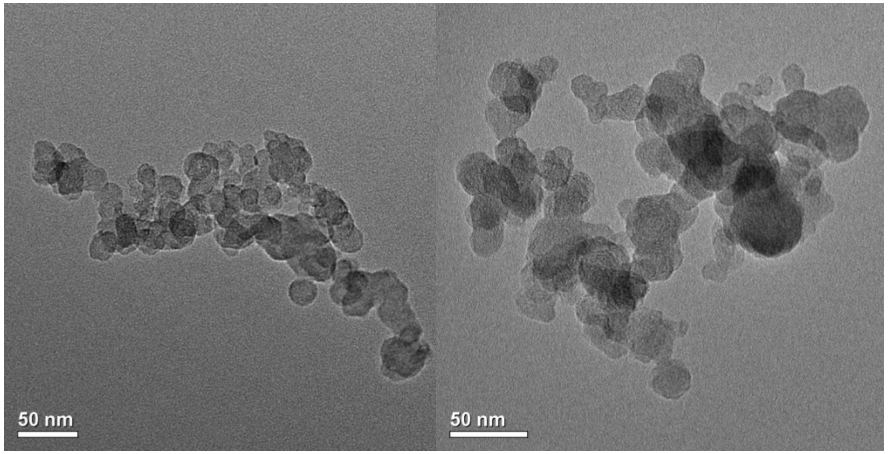
UNPA: Universal NanoParticle Analyzer

Primary particles in diesel particles

Engine load: light



Engine load: heavy



Engine load	Primary particle size from UNPA (nm)	Primary particle size from TEM (nm)
Light	29.5	23.2 ± 6.6
Heavy	24.2	23.9 ± 6.8

5. Conclusion

- Diesel particulate concentration and mean particle size increase with increasing engine load.
- Lower engine load or usage of the catalytic stripper lead to lower particle concentration, thus prolongs the loading time.
- Usage of the catalytic stripper results in very small changes in the particle size distribution, a less porous dust cake, and a higher pressure drop for a given mass loading.
- Theoretical model for the pressure drop gives rise to satisfactory fitting of the experimental data.

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