General Motors

Pacific Northwest
NATIONAL LABORATORY

Collaborative Research Laboratory

UW-Madison Engine Research Center

Micro-scale experimental evaluation of filtration of exhaust with low particle mass concentration

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Acknowledgements

- University of Wisconsin
  - Stephen Sakai, David Foster, Todd Fansler, Mike Andrie
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  - Paul Najt, Kushal Narayanaswamy, Arun Solomon
- Pacific Northwest National Laboratory
  - Alla Zelenyuk, Mark Stewart, David Bell, Jackie Wilson
- Filter sample suppliers

Overview

- Background & Objective
- Experimental Setup
- Characterization
  - Particulate matter (Number / Mass)
  - Filter (Porosity, Mean pore diameter, Permeability)
- Filtration experiments
- Results on trapped mass basis
- Summary

Background
Stages of filtration

Deep-Bed Filtration

- Particles retained throughout filter medium
- Length scale for particle capture changes by several orders of magnitude
- Low trapped mass → GPF

Cake Filtration

- Particles retained at media surface by filter cake
- Length scales remain practically unchanged
- Filtration efficiency > 99 %
- High trapped mass → DPF

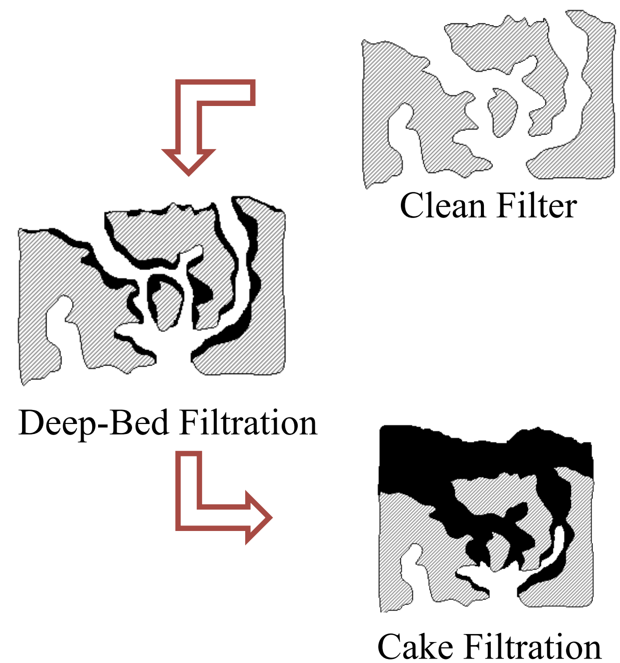


Fig. Different stages of filtration

Motivation & Objective

Motivation

- GPFs
  - → Higher exhaust temperature → More porous filters
  - → Low PM mass concentration → Longer deep bed filtration
- Experiments to help develop new deep-bed models to improve filter design

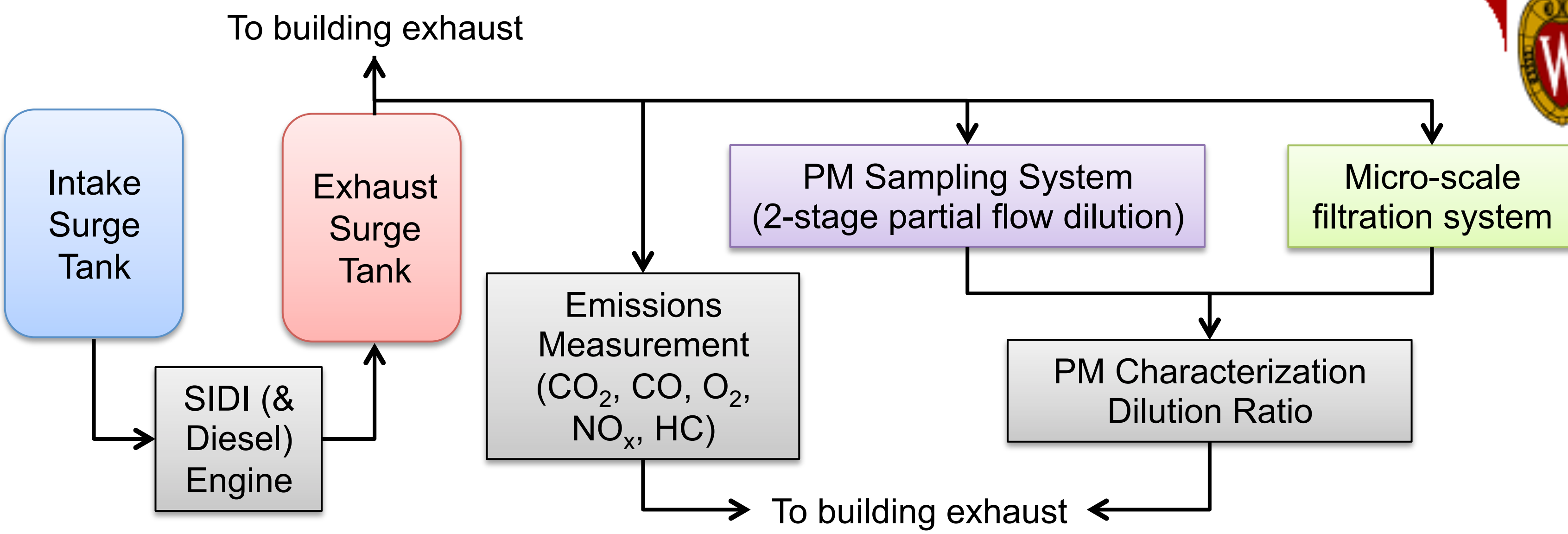
Objective

- Systematic study to determine impacts of
  - ➢ Inlet particle size distribution (PSD)
  - ➢ Trapped Mass
- Compare SIDI filtration results with diesel data

EXPERIMENTAL SETUP

Experimental Setup

Engine Configurations



	SIDI	Diesel (Reference)
Single cylinder adapted from	Opel 2.2 l Ecotec	Cummins N14
Displacement (l)	0.55	2.3
Compression Ratio	11.95	14.15
Bore (mm) x Stroke (mm)	86 x 94.6	140 x 152
Piston shape	Slightly domed	Mexican-hat
Injector	1 hole, Pressure swirl	8 hole (200 µm), XPI
Fuel	EPA Tier II EEE	# 2, ULSD

Experimental Setup

Filtration setup

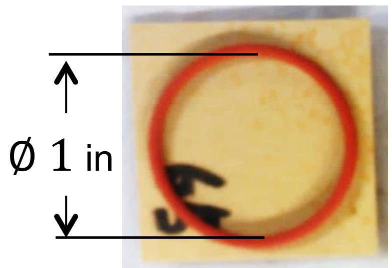
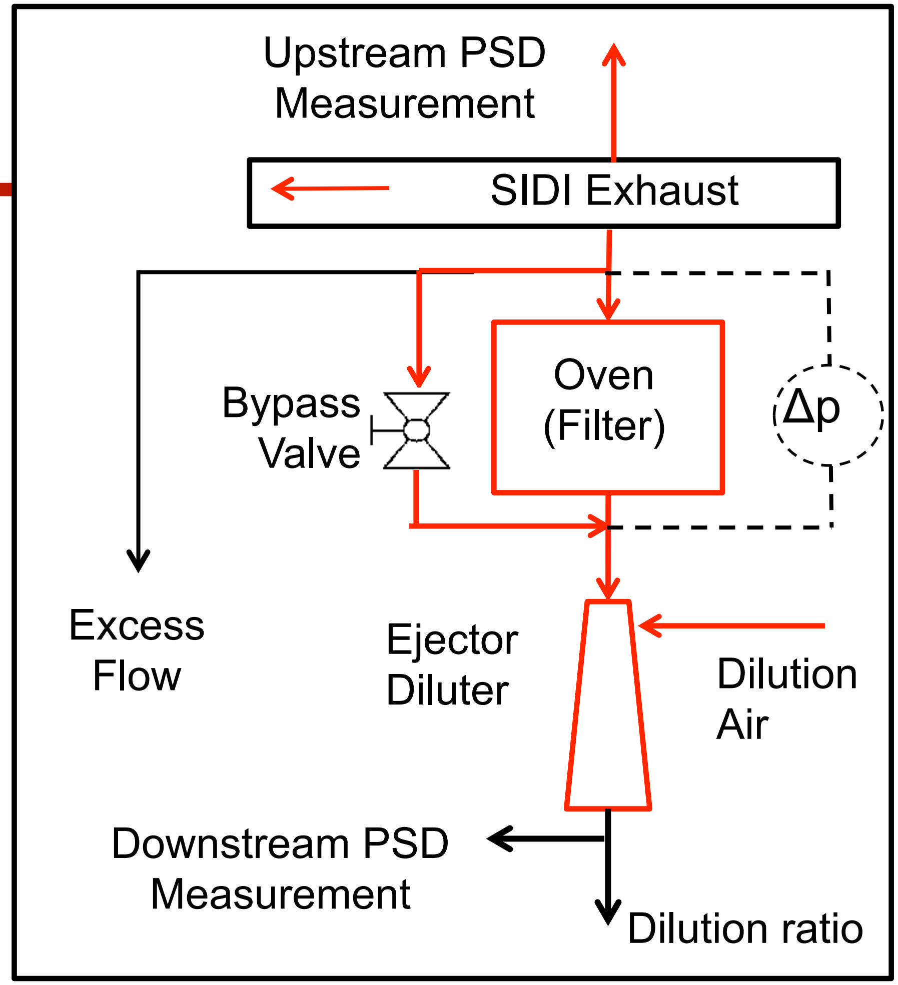


Fig. Wafer used in the EFA system (representative)



Real-Time Measurement of

- Upstream particle concentration
  - EEPS (SIDI)
  - Concentration fluctuated by ~2
- Downstream particle concentration
  - EEPS (Diesel)
  - SMPS (SIDI)
- Pressure drop
- Filtration velocity
  - 8 cm/s (Diesel)
  - 2.5 cm/s (SIDI)

EEPS – Engine exhaust particle sizer
SMPS – Scanning mobility particle sizer

PARTICULATE & FILTER CHARACTERIZATION

Exhaust Characterization

Number concentration

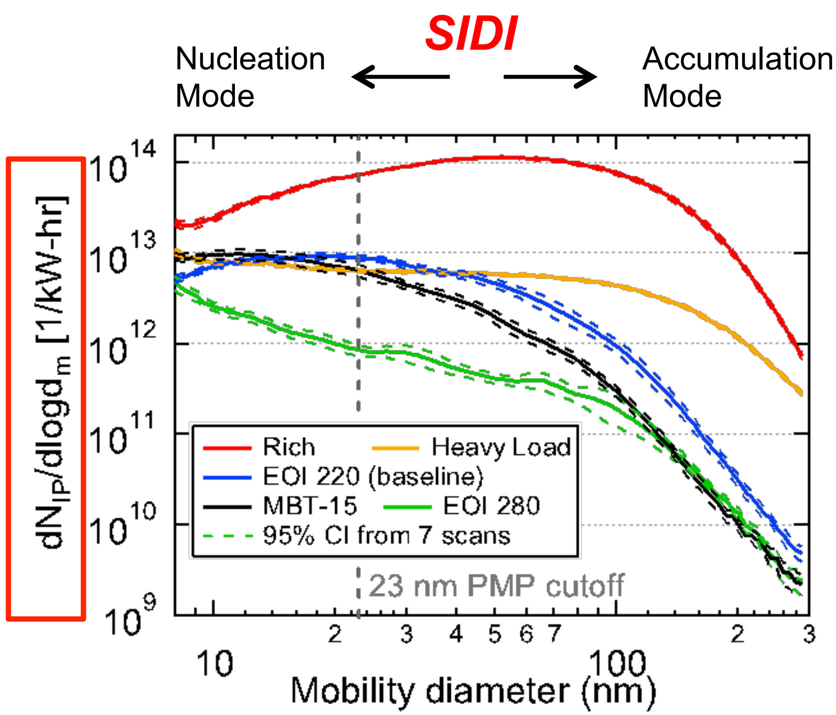


Fig. SIDI Particle Size Distribution (PSD)

$$[\#/kW-hr] = [\#/cc] * 1/\rho_{exhaut@SMPS} [cc/kg] * \dot{m}_{fuel} + \dot{m}_{air} [kg/hr] / Ind.\ Power [kW]$$

Exhaust Characterization

Number concentration

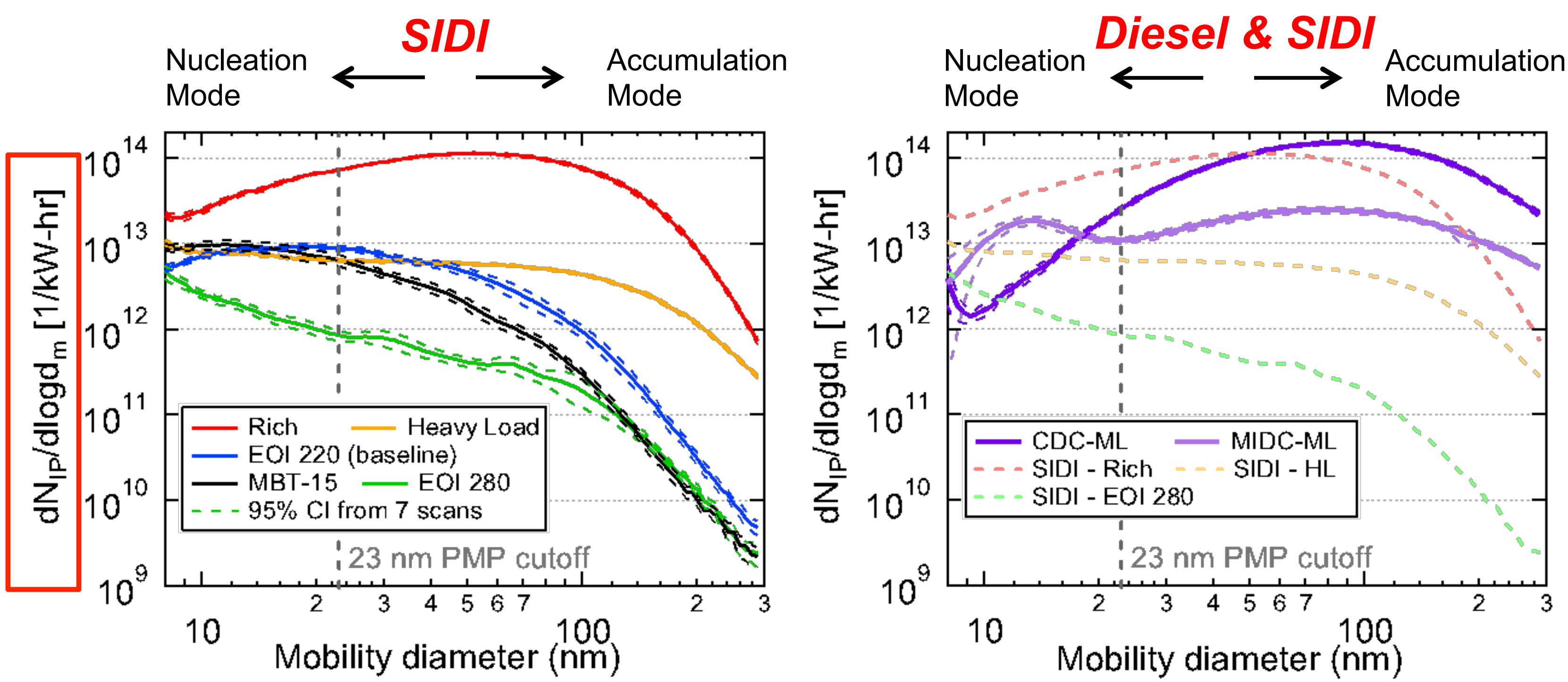


Fig. SIDI Particle Size Distribution (PSD)

$$[\#/kW-hr]=[\#/cc]*1/\rho_{exhaut@SMPS}\,[cc/kg]*\dot{m}_{fuel}+\dot{m}_{air}\,[kg/hr]/Ind.\,Power[kW]$$

CDC → Conventional diesel combustion
(1 inj. @ 850 bar)

MIDC → Multiple injection diesel combustion
(3 inj. @ 1200 bar)

ML → Medium load (~ 12 bar IMEP)

Exhaust Characterization

Mass concentration

- Gravimetric measurements performed using 47 mm filters on diesel exhaust
- Integrated particle size distribution (IPSD) method used to estimate mass concentration in SIDI exhaust

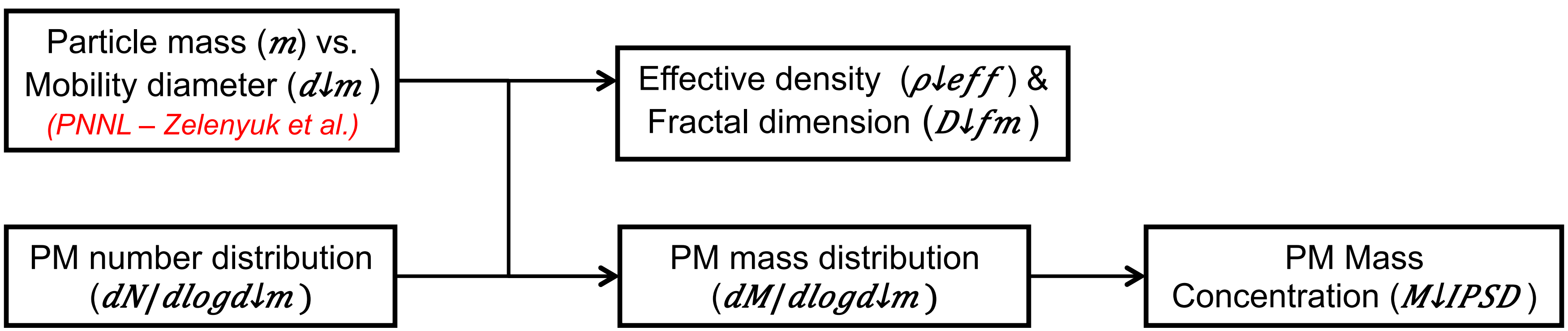


Fig. Schematic for IPSD method

$$M_{IPSD} = \int_{\log d_{m1}}^{\log d_{m2}} \left(m_{d_m} * dN/dlogd_m \right) dlogd_m$$

Exhaust Characterization

Mass-mobility relationship

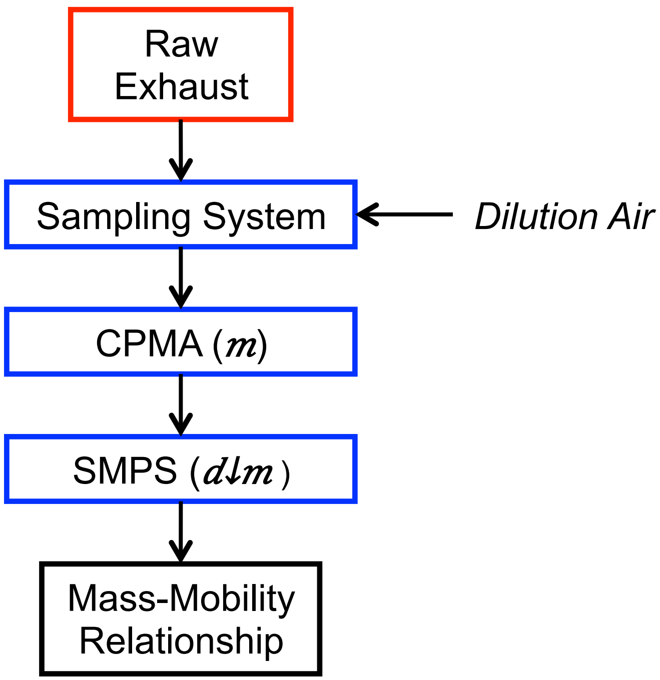


Fig. Experimental schematic to obtain mass-mobility relationship
(Zelenyuk et al.)

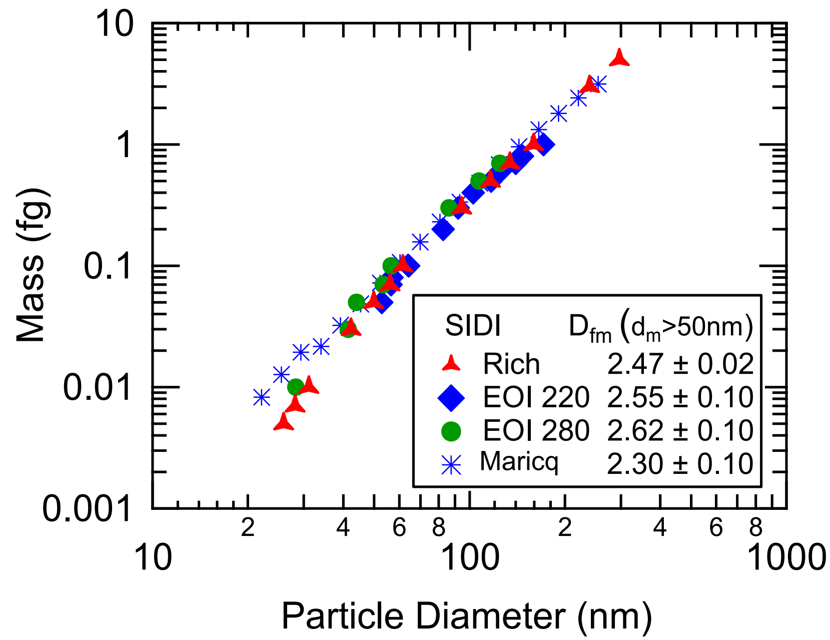


Fig. Mass-mobility relationship

- Weak dependence on operating condition
- Good Agreement with similar data in literature

CPMA – Centrifugal particle mass analyzer

Exhaust Characterization

IPSD applied to Diesel data

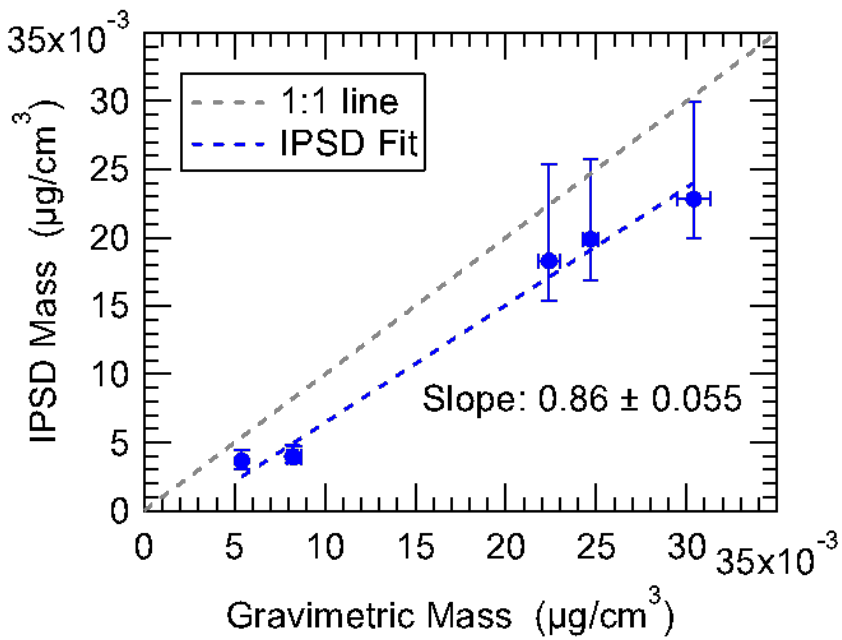


Fig. Estimated mass using IPSD method vs. gravimetric (Diesel)

- PSD extrapolated to 1000 nm using log-normal fit
- IPSD method used to estimate total mass concentration in diesel exhaust
  - Similar results using different mass-mobility fits
  - Underestimates mass concentration

Exhaust Characterization

Estimated Mass Concentrations

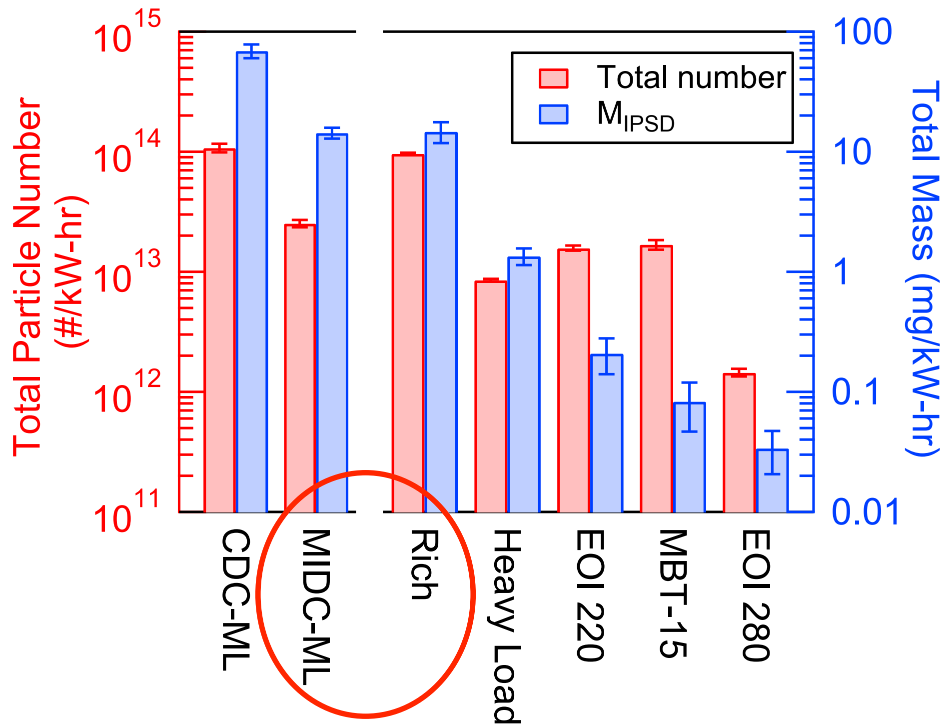


Fig. Total particle number & mass concentrations

- Estimated mass spans several orders of magnitude
- Little correlation between number and mass concentration trends
- Only Rich SIDI operation comparable with Diesel conditions

Filter Characterization

Sample to sample variation

- Different filters from same batch used for each experiment

- Intrusion porosimetry performed on filter sample

Table. Filter properties

Material	Mean Pore Diameter (μm)		Porosity (%)		Thickness (mm)
	A	***B***	***A***	***B***	
Cordierite	14	15.5	43.6	42.5	0.98

A → Manufacturer Specifications
B→ Intrusion porosimetry on random sample

Filter Characterization

Sample to sample variation

- Different filters from same batch used for each experiment
- Intrusion porosimetry performed on filter sample
- Filter permeability (k) measured to identify sample to sample differences.

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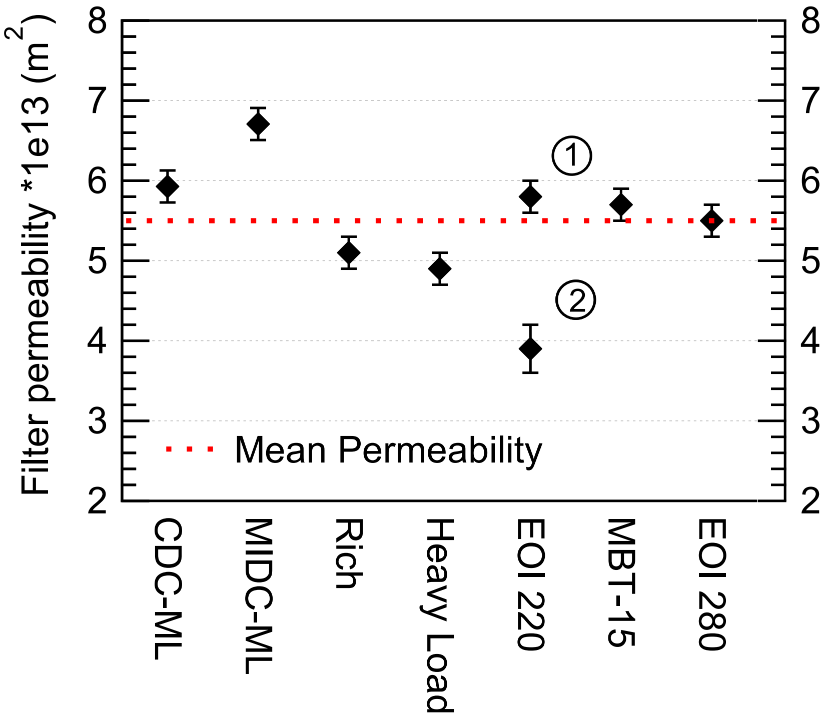


Fig. Sample to sample variability between wafers used for each experiment

$$k = \mu * t * v / \Delta P$$

μ → *viscosity of the fluid*
t → *filter thickness*
v → *flow velocity through the filter*
ΔP → *pressure drop across the filter.*

FILTRATION EXPERIMENTS

Filtration Experiments

Scaled pressure drop (SPD)

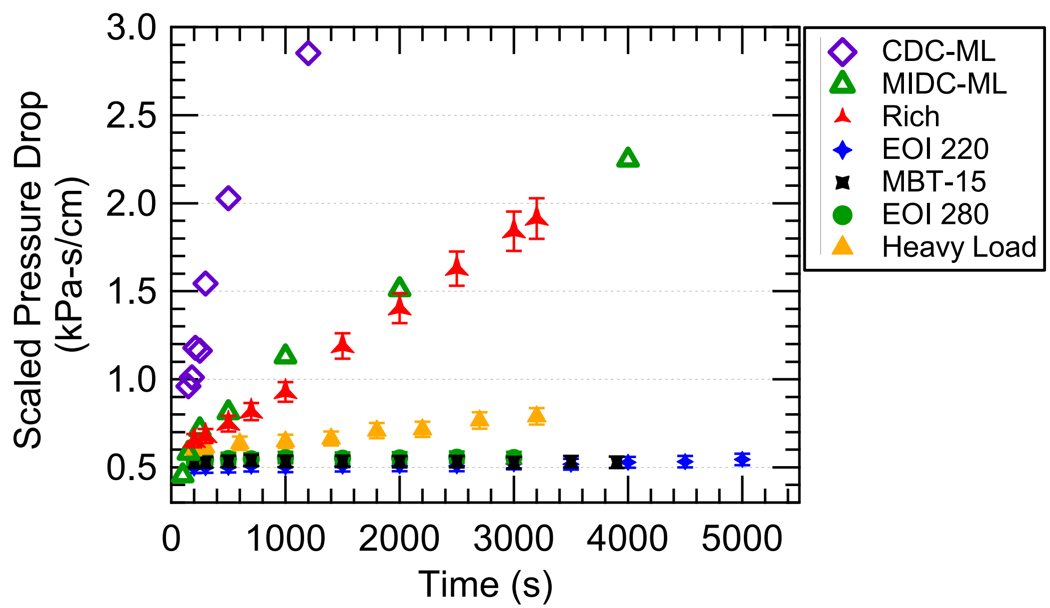


Fig. Evolution of scaled pressure drop with loading time

■$Scaled@Pressre\ Drop = Pressure\ Drop/Filtration\ Velocity$

- HDD → Clear distinction between wall loading and cake build up regions
- SIDI → Only the Rich & HL conditions showed increase in SPD
- No distinct transition from wall loading to cake buildup observed for the Rich case
- Holder effect was 0.11±0.1 (kPa-s/cm)

Filtration Experiments

Scaled pressure drop (SPD)

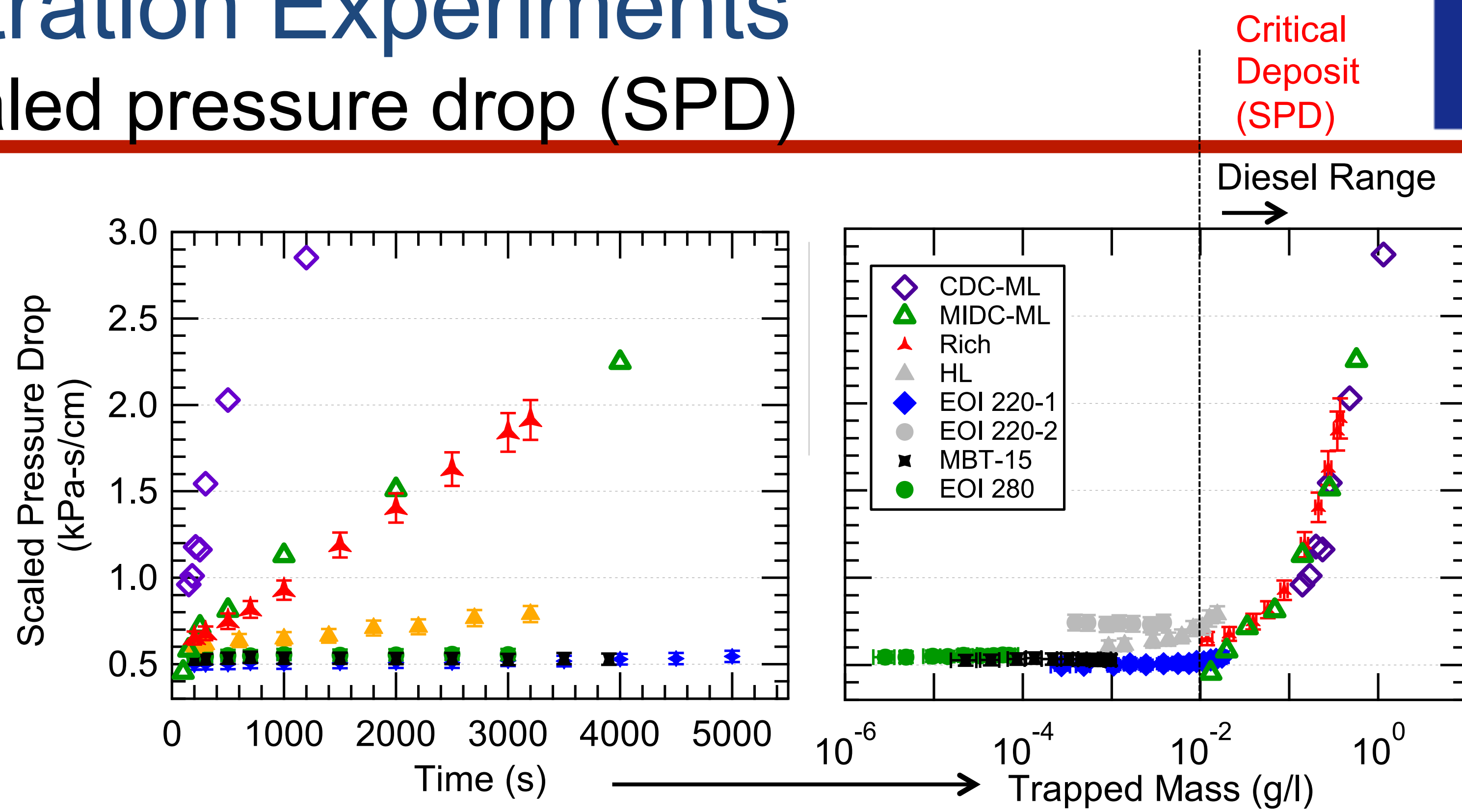


Fig. Evolution of scaled pressure drop with loading time & trapped mass

$$\text{Trapped Mass}(t) = \int_0^t \left([M_{IPSD,in} - M_{IPSD,out}] * v * GFA \right) dt$$

Assumed geometric filtration area (GFA) of 1.1 [m^2/l]

- Consistent overlap between SIDI & Diesel results
- Minimum deposit before SPD changes → *Critical deposit*
- Outliers → HL & EOI 220-2

Filtration Experiments

Filtration Efficiency (FE)

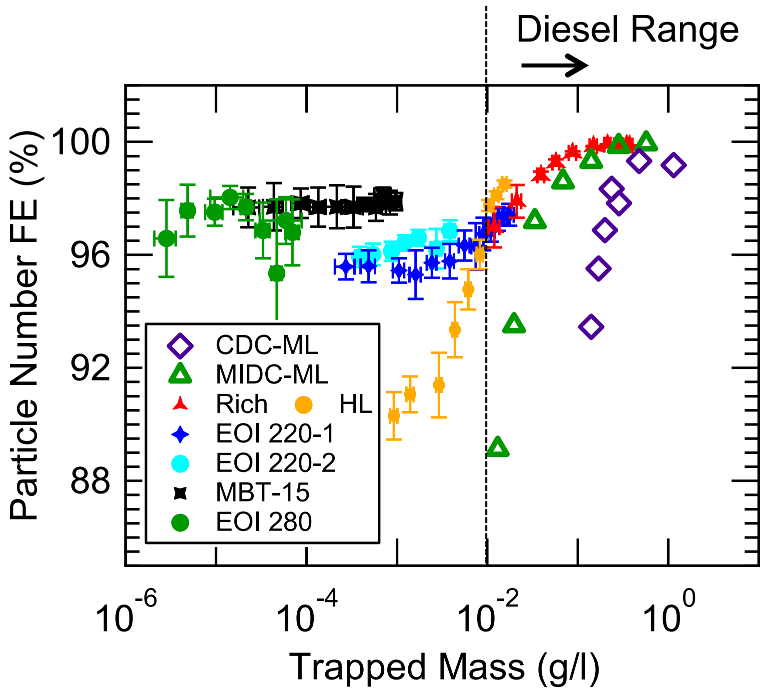


Fig. Evolution of particle number based filtration efficiency with time

- Number based FE
  - Relatively high
  - Dominated by smaller particles
  - No consistent overlap between conditions

- Possible sensitivity to
  - Filter sample variability
  - Inlet size distribution
  - Experimental conditions & artifacts

Filtration Experiments

Filtration Efficiency (FE)

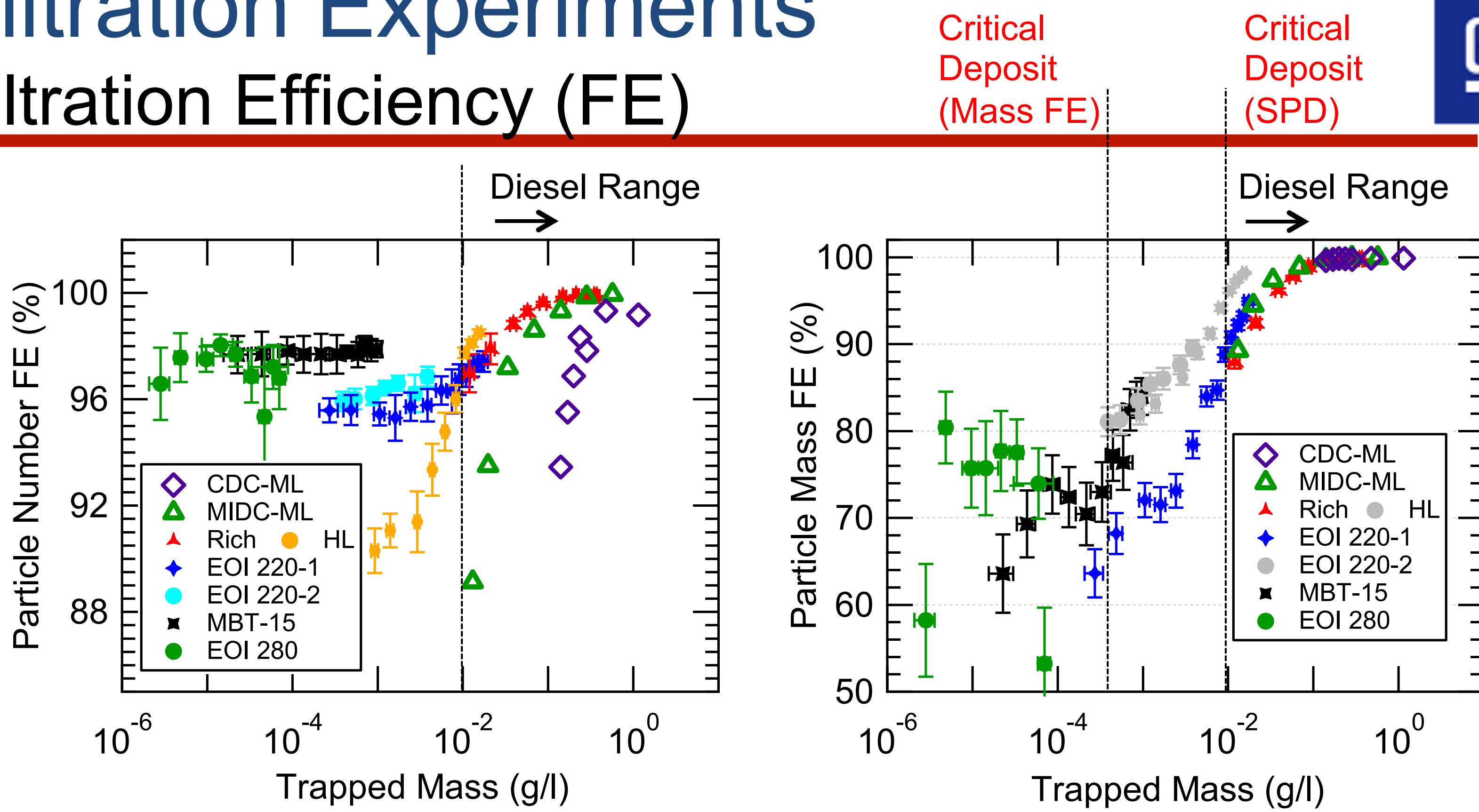


Fig. Evolution of particle number (left) and mass(right) based filtration efficiency with trapped mass

- Consistent overlap between SIDI & Diesel mass based FE.
- Critical deposit for mass based FE different from that for NPD
- Outliers → HL & EOI 220-2

Filtration Experiments

Outliers

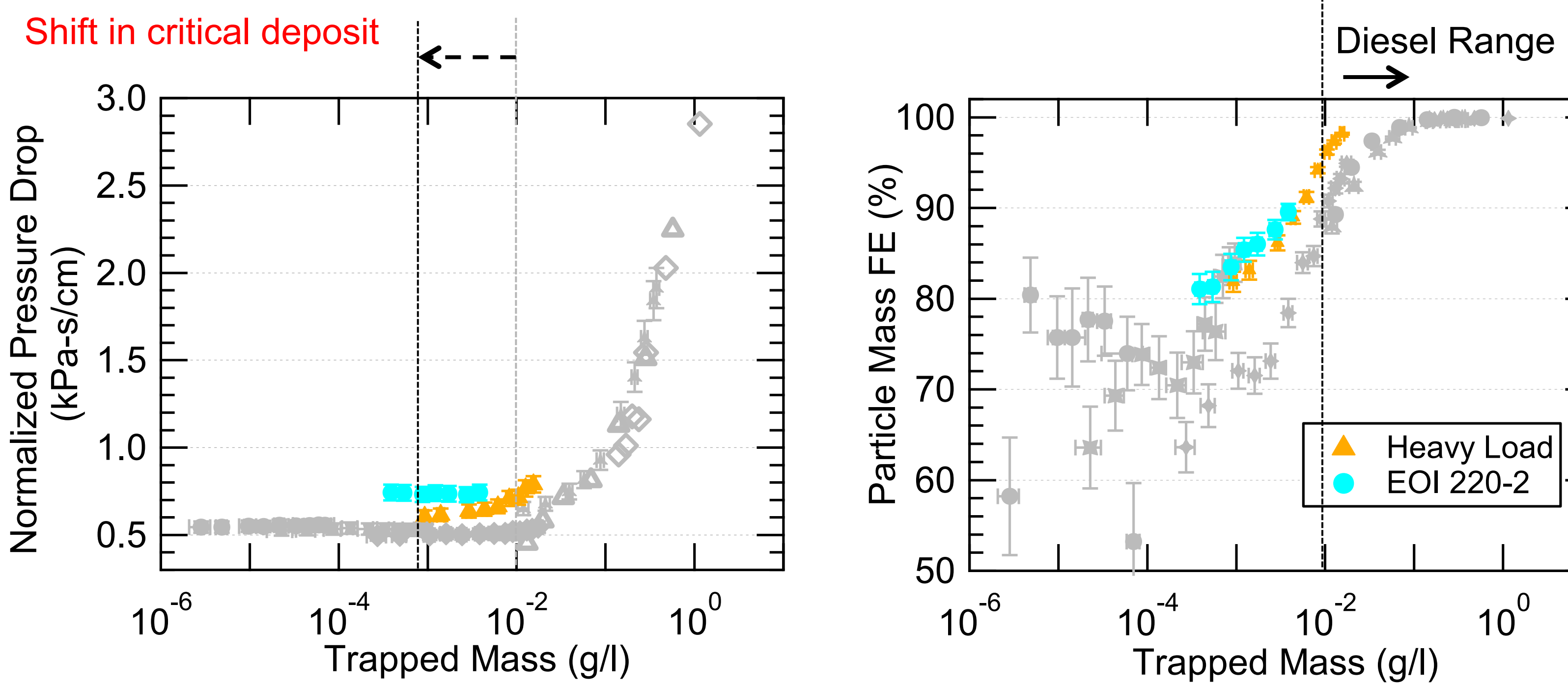


Fig. Evolution of scaled pressure drop (left) and mass (right) based filtration efficiency with trapped mass

- HL experiments at 1.9 cm/s & 95°C
- EOI 220-2 on filter sample with low permeability
- Possible shift in critical deposit observed
- Method shows sensitivity to experimental conditions and sample variability

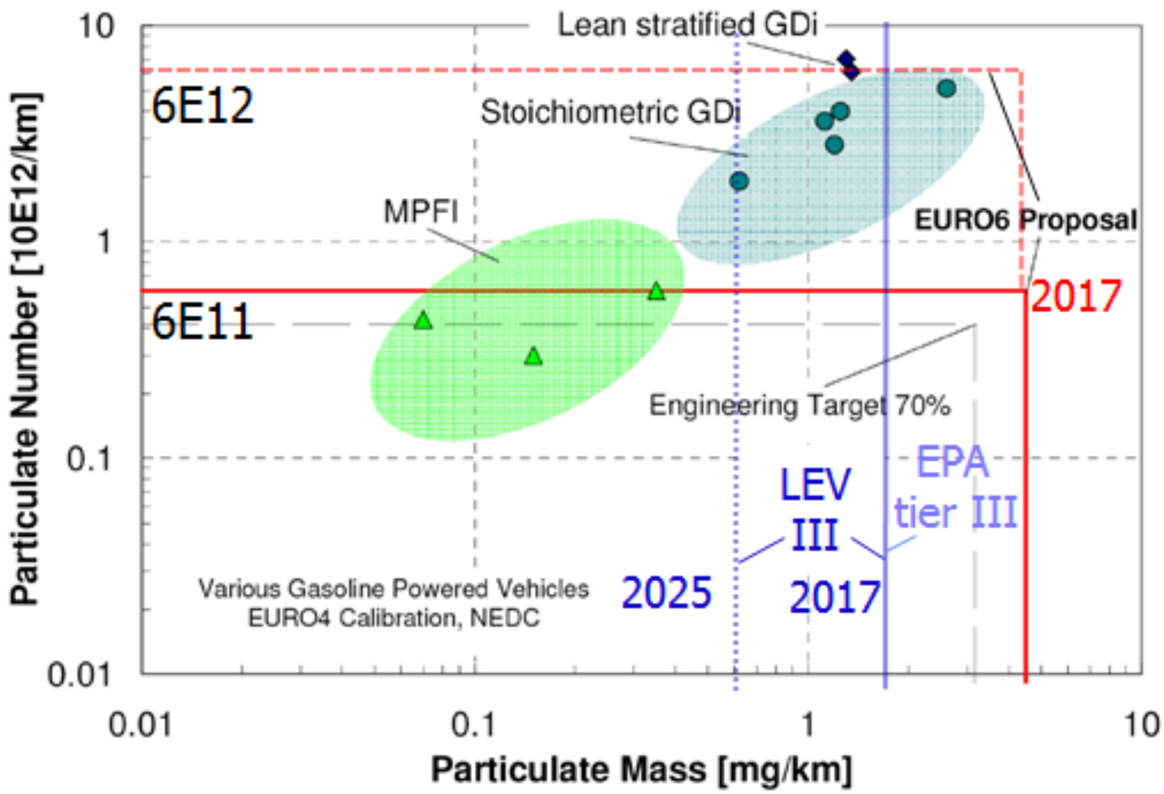
Filtration of SIDI Particulate
Summary and Conclusions

- Micro-scale filtration experiments on DPF-like filter samples
- IPSD method
  - Used mass-mobility data from SIDI exhaust
  - Reasonable agreement with HDD filter measurements
  - Estimate trapped mass in filter
- Filtration performance (SPD, and mass based FE) evolution showed consistent overlap
- Method sensitive to small changes in filter properties and loading conditions

Thank You. Questions?

BACKUP SLIDES

Background
PM Regulations



Particulate number versus mass per km for SI engine technologies. Adapted from [1]. **US regulations are not based on NEDC*

- Tightening PM regulations on SIDI engines worldwide
- Particle number regulations represent a significant challenge in Europe
- Particle mass emissions become challenging in the US for EPA tier III and LEV III

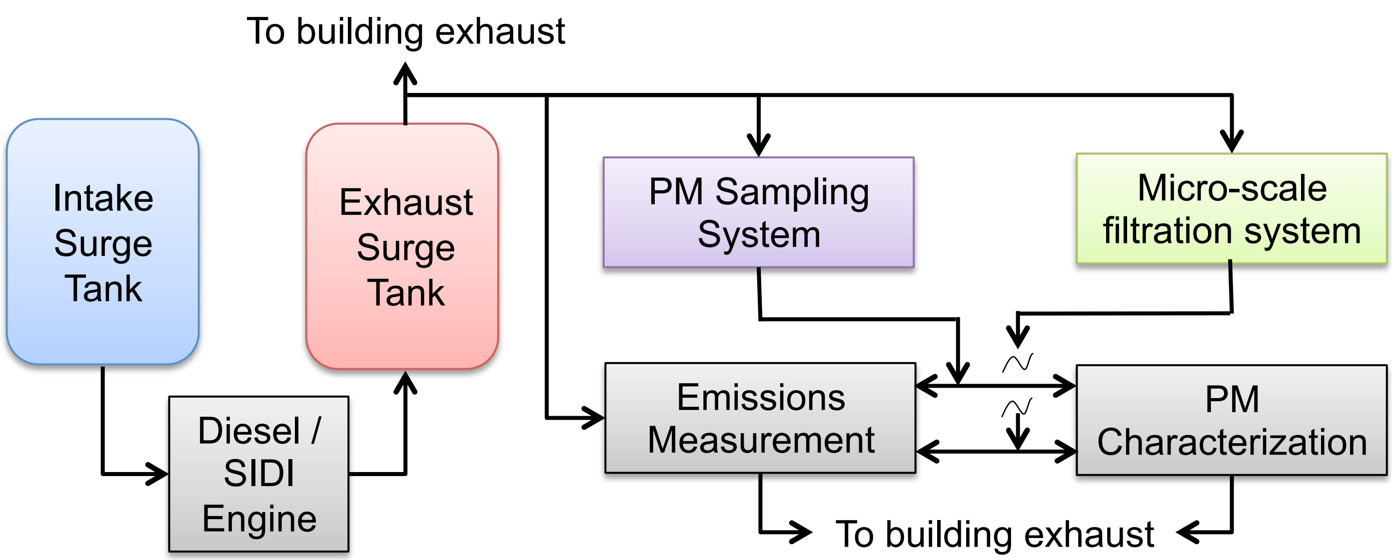
Improved understanding of SIDI PM characteristics and filtration needed

→ Enable improved after-treatment system design

[1] Piock et al., SAE 2011-01-1212

Experimental Setup

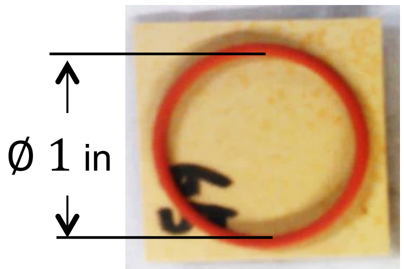
Sampling and characterization instruments



	Heavy Duty Diesel	SIDI
Emissions Measurement	Nicolet FTIR	Horiba gas bench
PM Sampling system	Dekati, 2-stage mini-dilution tunnel (MDT)	
PM characterization – Particle Size Distributions	TSI-3080 SMPS, 3081 I-DMA, 3010 CPC	
PM characterization – Particle mass	47 mm gravimetric	CPMA
Temperature (Sampling location / dilution probe / primary dilution / secondary dilution / characterization instruments)	265 / 175 / 100 / Ambient / 52	260 / 265 / 235 / Ambient / 52
Sample dilution ratio / Estimation method	~ 20 / CO2 conc.	

Experimental Setup

Filtration setup



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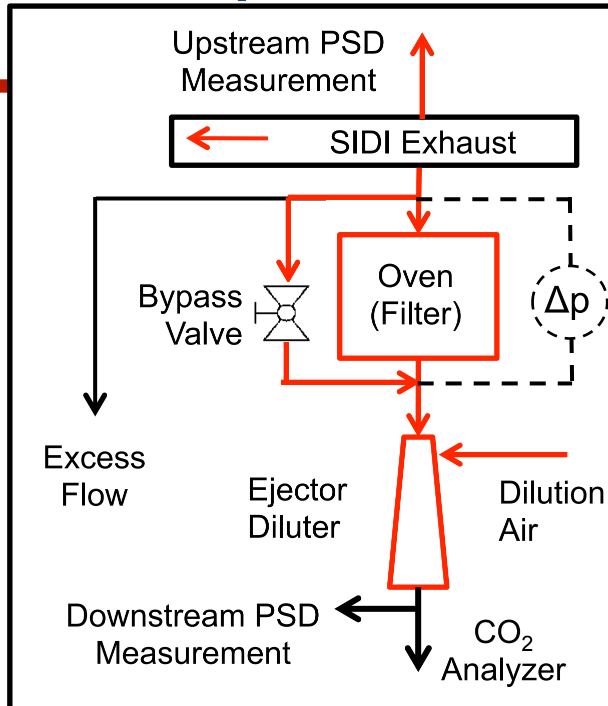
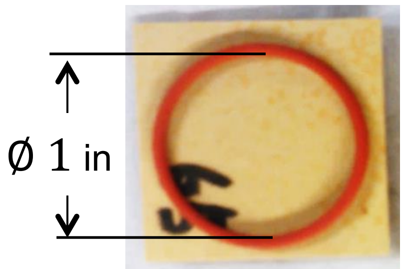


	SIDI (EFA)	Diesel (DEFA)
Temp. at sampling location (°C)	~ 260	~ 265
Filtration conditions	**2.4 (cm/s) @ 175 (°C)**	8 (cm/s) @ 175 (°C)
Upstream / Downstream PSD measurement	**EEPS / SMPS**	None / EEPS
Downstream dilution setup	Ejector diluter	Cross flow
Downstream dilution temp. (°C)	175	100
Downstream dilution ratio / Estimation method	~ 15 / CO2 conc.	~ 14 / Mass flow

Experimental Setup

Filtration setup



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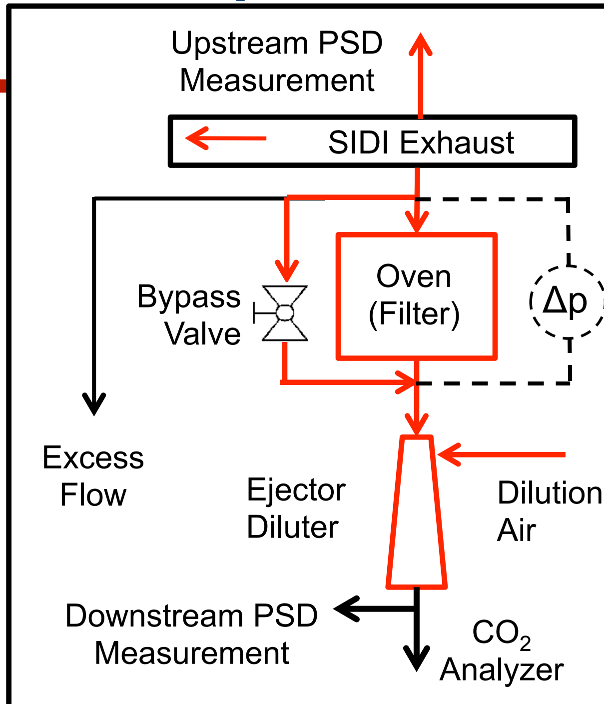

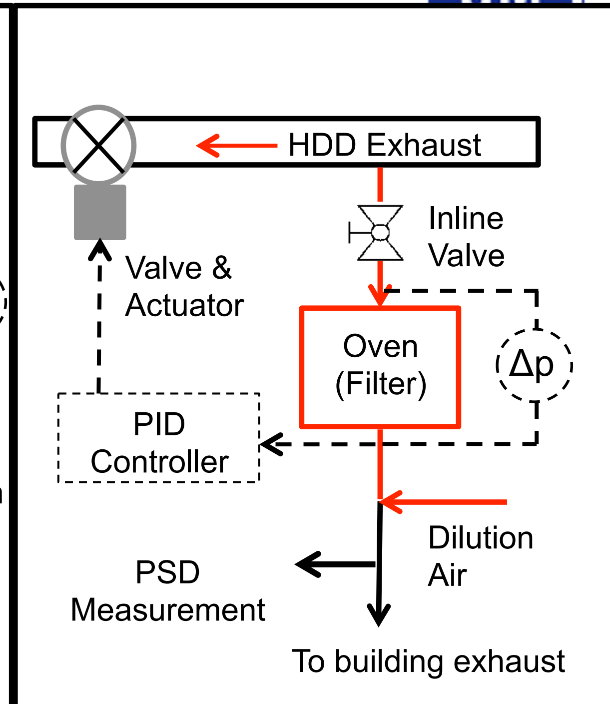

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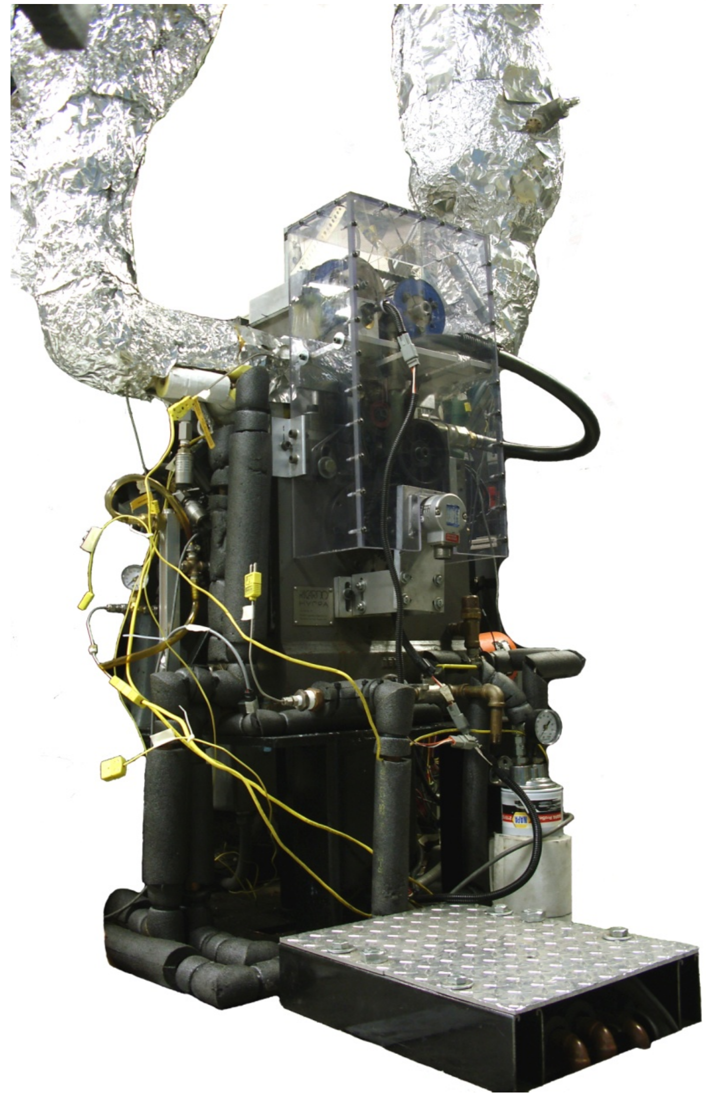
Downstream dilution temp. (°C)	175	100
Downstream dilution ratio / Estimation method	~ 15 / CO2 conc.	~ 14 / Mass flow

Experimental Setup
Engine Information

- Single cylinder SIDI engine
  - LCH 2.2L Ecotec engine used by Opel in Europe
- 4-valve pentroof head with slightly domed flat-top piston
- Stoichiometric SIDI architecture

Compression Ratio	12.0
Bore [mm]	86.0
Stroke [mm]	94.6
Displacement [cm^3]	550
Connecting Rod Length [mm]	152.4
Intake Valve Open [CAD]	-360
Intake Valve Close [CAD]	-150
Intake Valve Lift [mm]	9.9
Exhaust Valve Open [CAD]	+155
Exhaust Valve Close [CAD]	+360
Exhaust Valve Lift [mm]	9.9



Characterization

Operating conditions

Engine		SIDI					HDD	
Condition		EOI 280	EOI 220	MBT -15	Rich	Heavy Load	CDC-ML	MIDC-ML
Load	(bar-IMEP)	3.5	3.3	2.7	3	6.5	11.5	12.1
Speed	(rpm)	2100	2100	2100	2100	2100	1200	1200
Fuel injection pressure	(bar)	110	110	110	110	110	850	1200
Injection timings	(aTDC)	-280	-220	-220	-220	-220	-7	-25,-8,-7
Spark timing	(aTDC)	-25	-25	-10	-25	-25	-	-
Air/ fuel ratio	-	15	15	15	13	15	22.3	27
Intake manifold pressure	(kPa-abs)	35	35	35	31	60	149	167
Exhaust back pressure	(kPa-abs)	102	102	102	102	102	165	165
Exhaust temperature	(°C)	593	592	700	560	630	620	508

Particulate Characterization
SIDI Operating Conditions

Condition →	Late Inj.	Ret. Spark	Early Inj.	Rich	Heavy Load
Speed (RPM)	2100	2100	2100	2100	2100
Load – $IMEP_{gross}$ [kPa]	334 ± 5	265 ± 5	350 ± 3	300 ± 5	650 ± 10
CA 50 (CAD)	8 ± 0.5	*	8.8 ± 0.5	6.7 ± 0.5	12 ± 0.5
Equivalence Ratio (Φ)	0.98	0.98	0.98	1.13	0.98
IMAP [kPa]	35	35	35	31	60
Injection pressure [MPa]	11	11	11	11	11
Spark Timing [CAD]	-26	-11	-26	-26	-15
Injection Timing [CAD]	-220	-220	-280	-220	-220

Changes relative to baseline (Late Inj.)

Emissions

CO_2 [% Volume]	13.7	14.6	14.6	12.1	13.7
O_2 [% Volume]	1.3	0.8	1.1	0.6	1.2
CO [% Volume]	1.0	0.35	0.55	4.2	0.98
HC [ppm]	670	300	1000	1600	500
NO [ppm]	1100	300	2200	730	1500

Particulate Characterization
Comparison to Diesel Operation

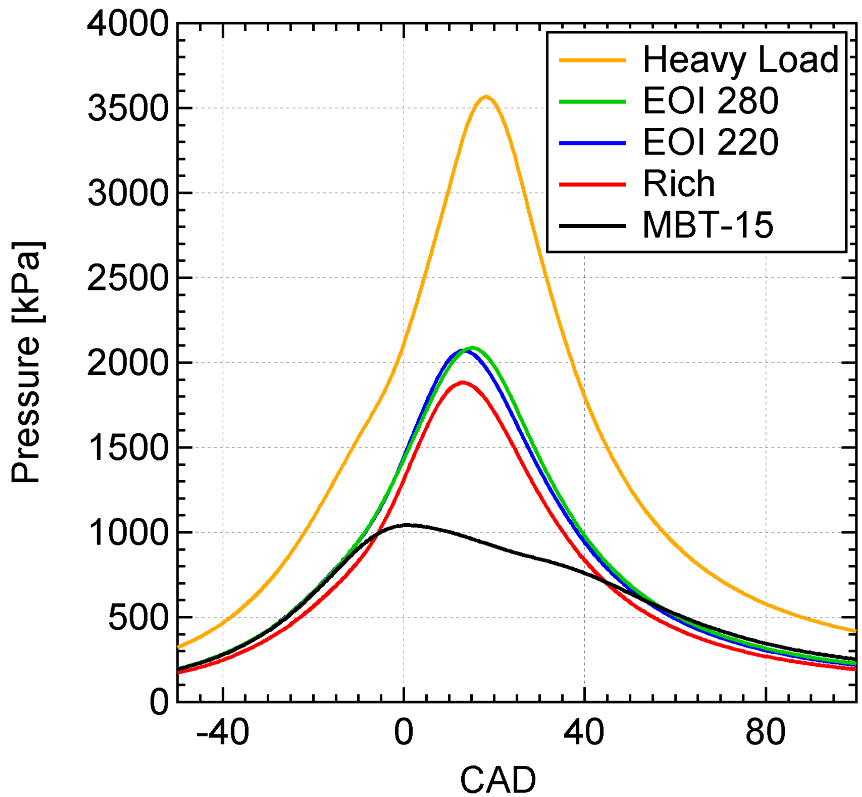
Diesel engine* operating conditions for comparison to SIDI data

Mode	*CDC Medium Load (ML)*	*MIDC Medium Load (ML)*	*MIDC Low Load (LL)*
Speed (rpm)	1200	1200	1200
IMEP (bar)	11.45	12.12	3.5
Intake Pressure (kPa)	149	167	158
Injection Pressure (bar)	850	1200	1200
# of Injections	1	3	2
Injection Timing [CAD]	-7	-25, -8, -7	-8, -7
Injected Fuel Mass [mg]	151.25	30, 15, 106.25	15, 61
A/F Ratio	22.3	27	67.9

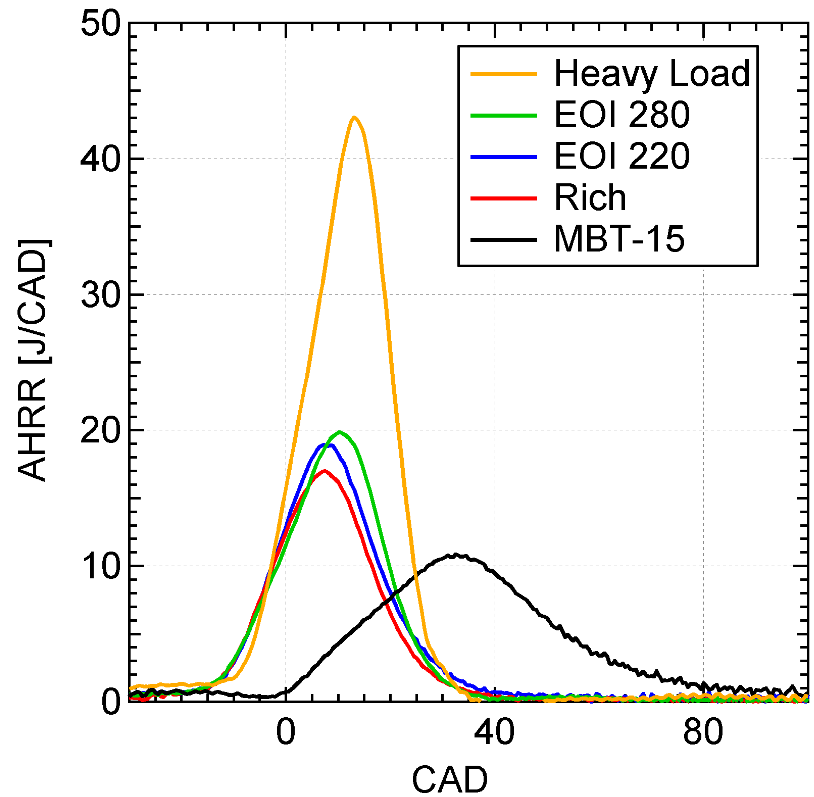
*Engine used for measurements was a single-cylinder Cummins N14 heavy-duty diesel engine, displacement = 2.3 L, 8 x 200 μm hole electronic unit injector

CDC = Conventional Diesel Combustion   MIDC = Multi-Injection Diesel Combustion

Particulate Characterization
SIDI Operating Conditions



In-cylinder pressure for five different SIDI operating conditions



Net apparent heat release rate for five different SIDI operating conditions

Exhaust Characterization

Particle Size Distribution (PSD)

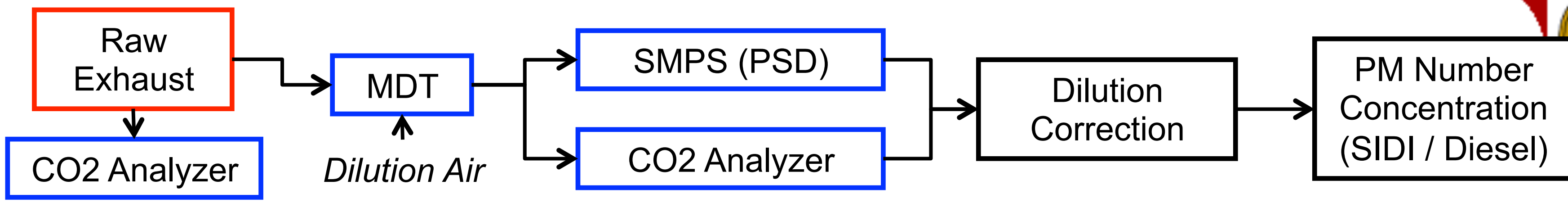
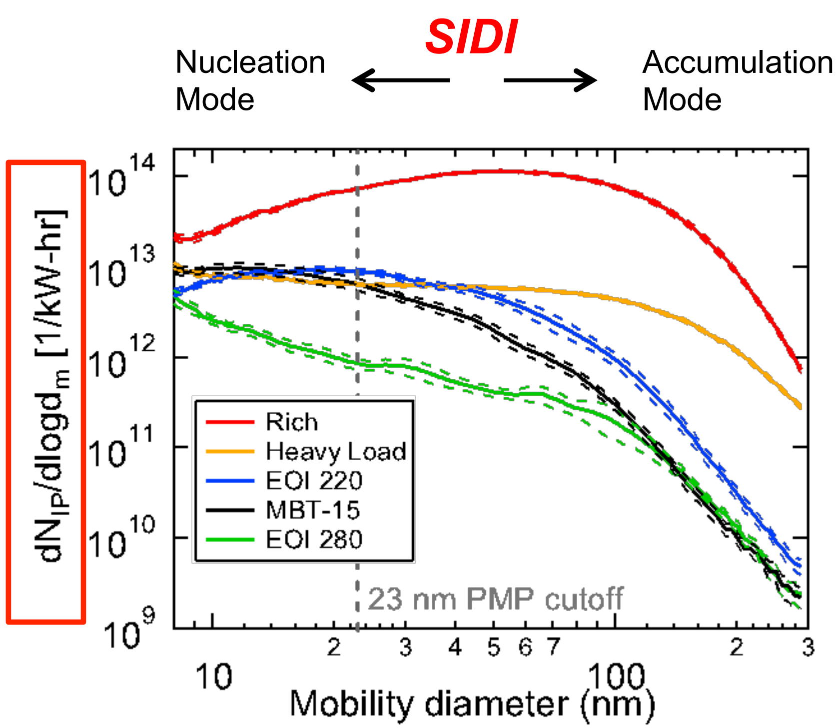
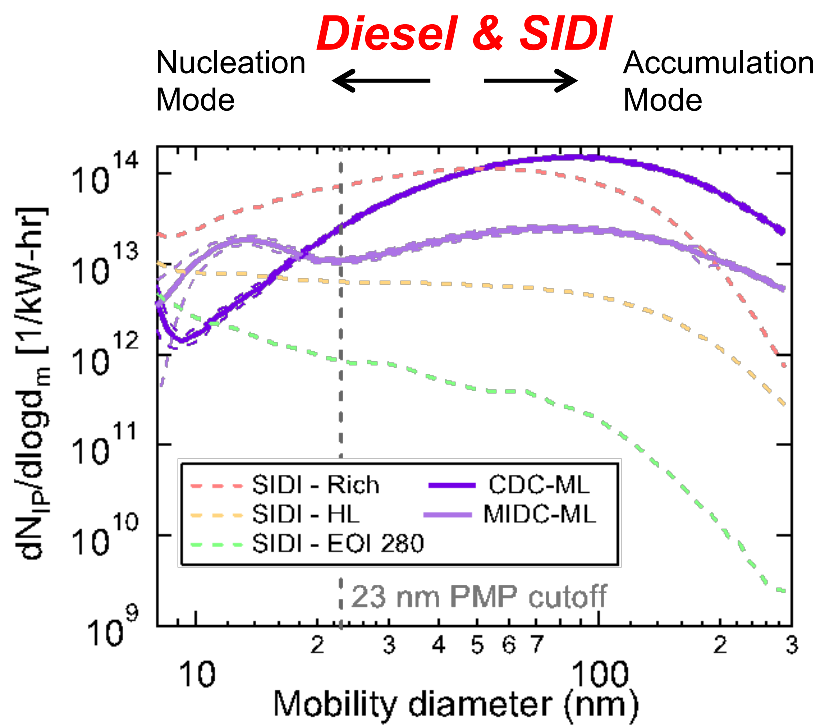


Fig. Schematic for SIDI & Diesel PSD measurements





$$[\#/kW-hr\ ]=[\#/cc\ ]*1/\rho\downarrow exhaut\ \ [c$$

Particulate Characterization

Summary

- Wide dynamic range of size distribution possible during SIDI operation
- SIDI particle number and mass are well below typical diesel values as expected
- SIDI particulate is generally more compact (larger D_f) than diesel particulate
- Wide range of particle shapes are present under certain conditions
- SIDI particles contain a large fraction of organics ~40-60% bound into the particulate
  - Organics not due to volatile particles

Characterization results provide insights into particulate formation and boundary conditions for filtration experiments

Filtration Experiments

Experimental conditions

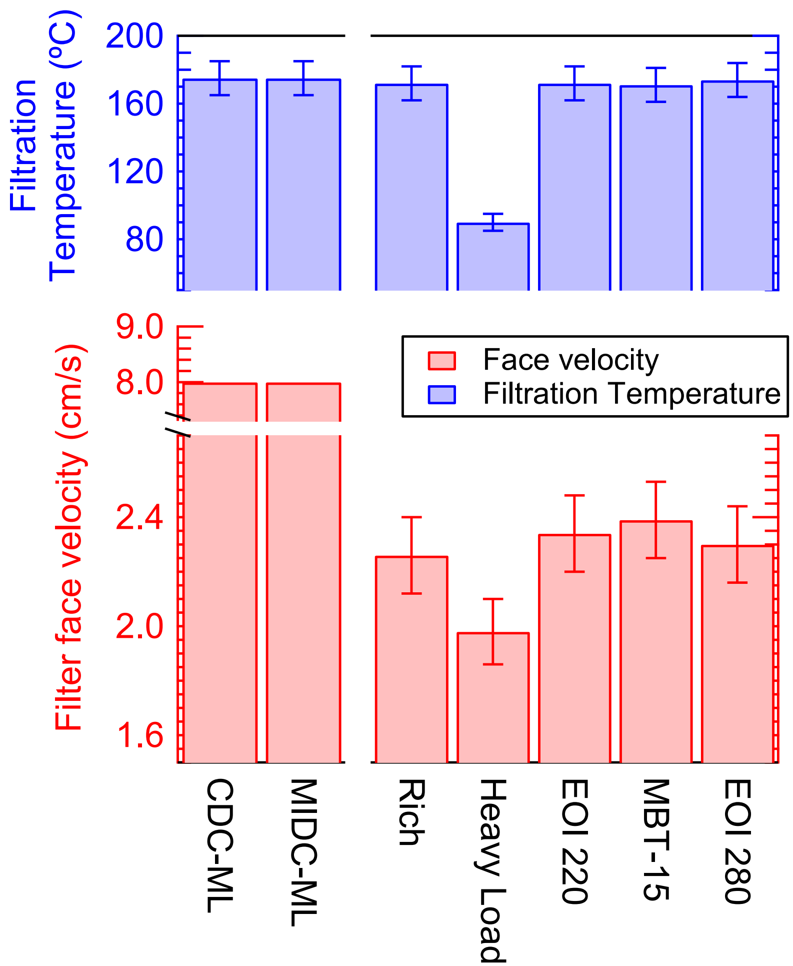


Fig. Comparison of experimental conditions

Real time measurements of

- Upstream PSD
- Downstream PSD
- Pressure drop
- Downstream pressure
- Filtration velocity (from temperature & dilution ratio)

$$Trapped\ Mass\ (t) = \int_0^t ([M_{PSD,in} - M_{PSD,out}] * v * GFA)\, dt$$

Assumed geometric filtration area (GFA) of 1.1 [m^2/l]

 Collaborative Research Laboratory

Filtration Experiments

Schematic

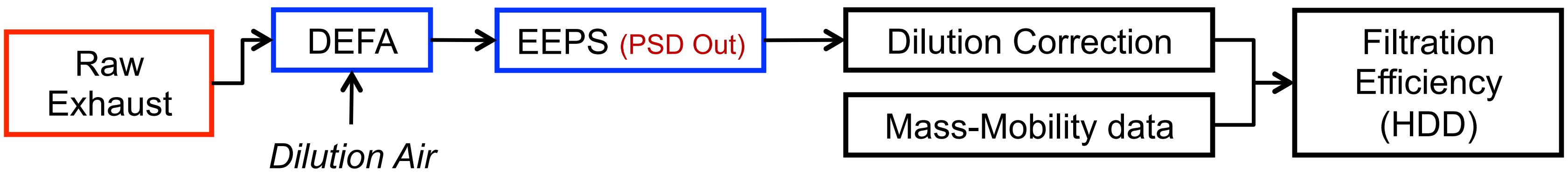


Fig. Filtration experiment layout (HDD)

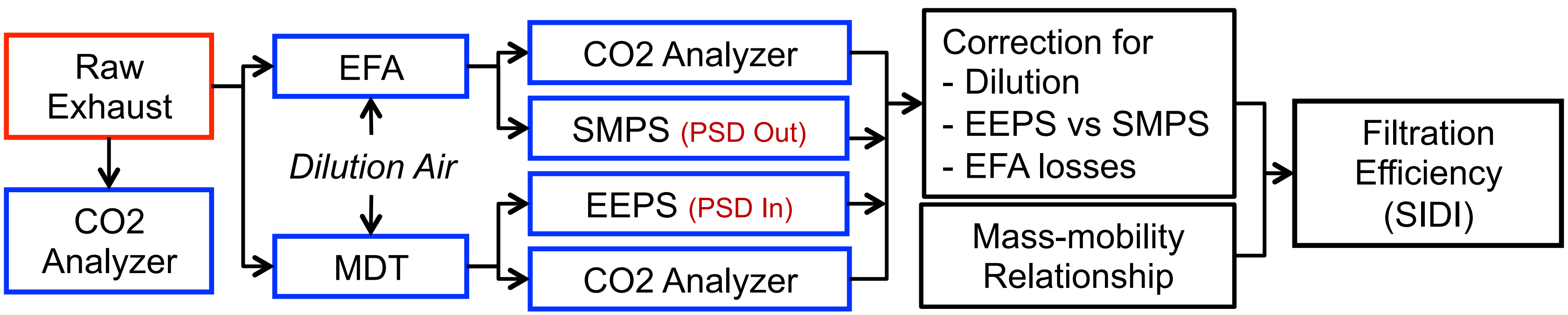


Fig. Filtration experiment layout (SIDI)

$$Trapped\ Mass\,(t) = \int_0^t ([M_{PSD,in} - M_{PSD,out}] * v * GFA)\,dt$$

Assumed geometric filtration area (GFA) of 1.1 [m^2/l]

Filtration Experiments

Penetration

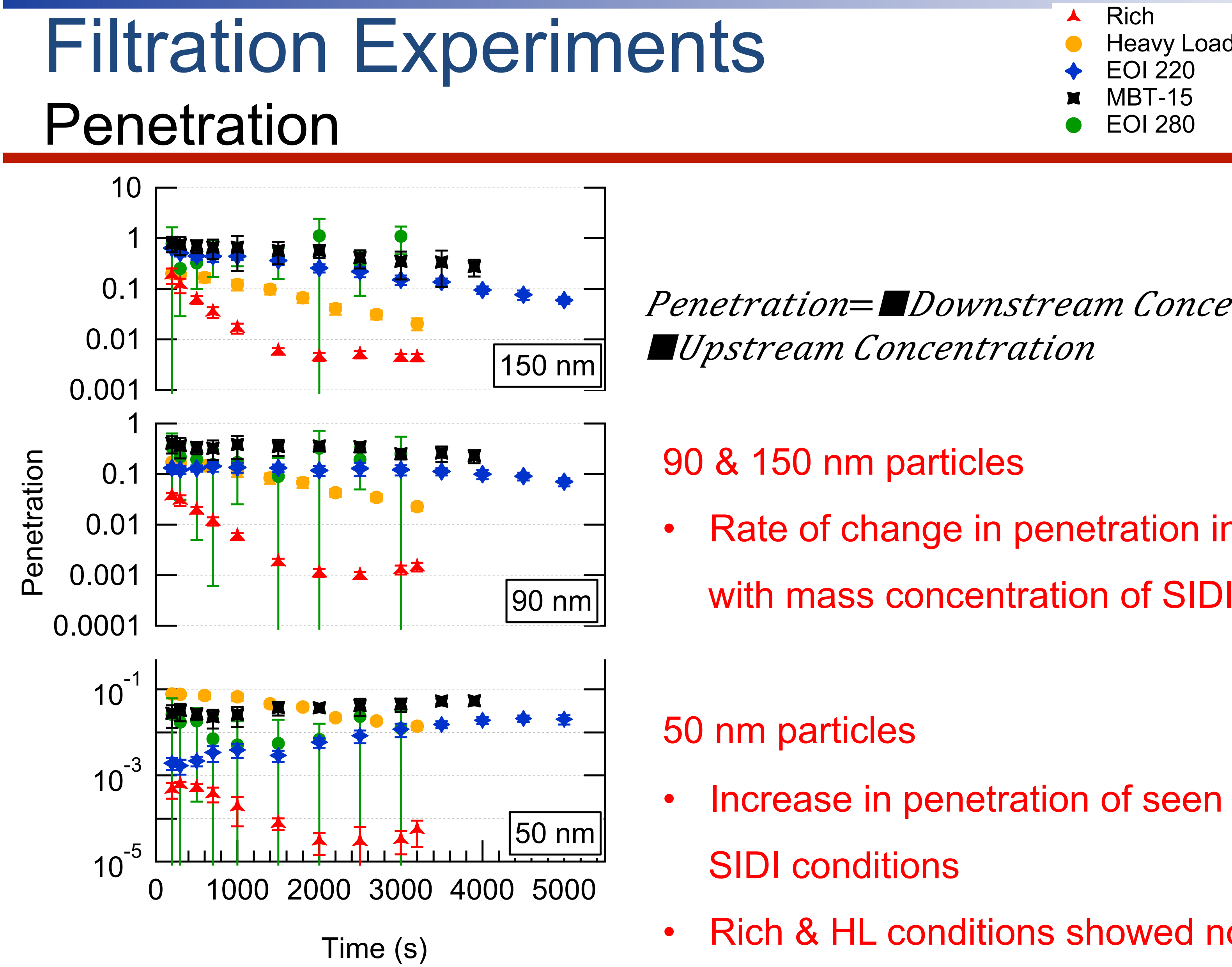


Fig. Evolution of particle penetration with loading time

Penetration=Downstream Concentration / Upstream Concentration

90 & 150 nm particles

- Rate of change in penetration increases with mass concentration of SIDI condition

50 nm particles

- Increase in penetration of seen for some SIDI conditions
- Rich & HL conditions showed no increase

Filtration Experiments

Penetration

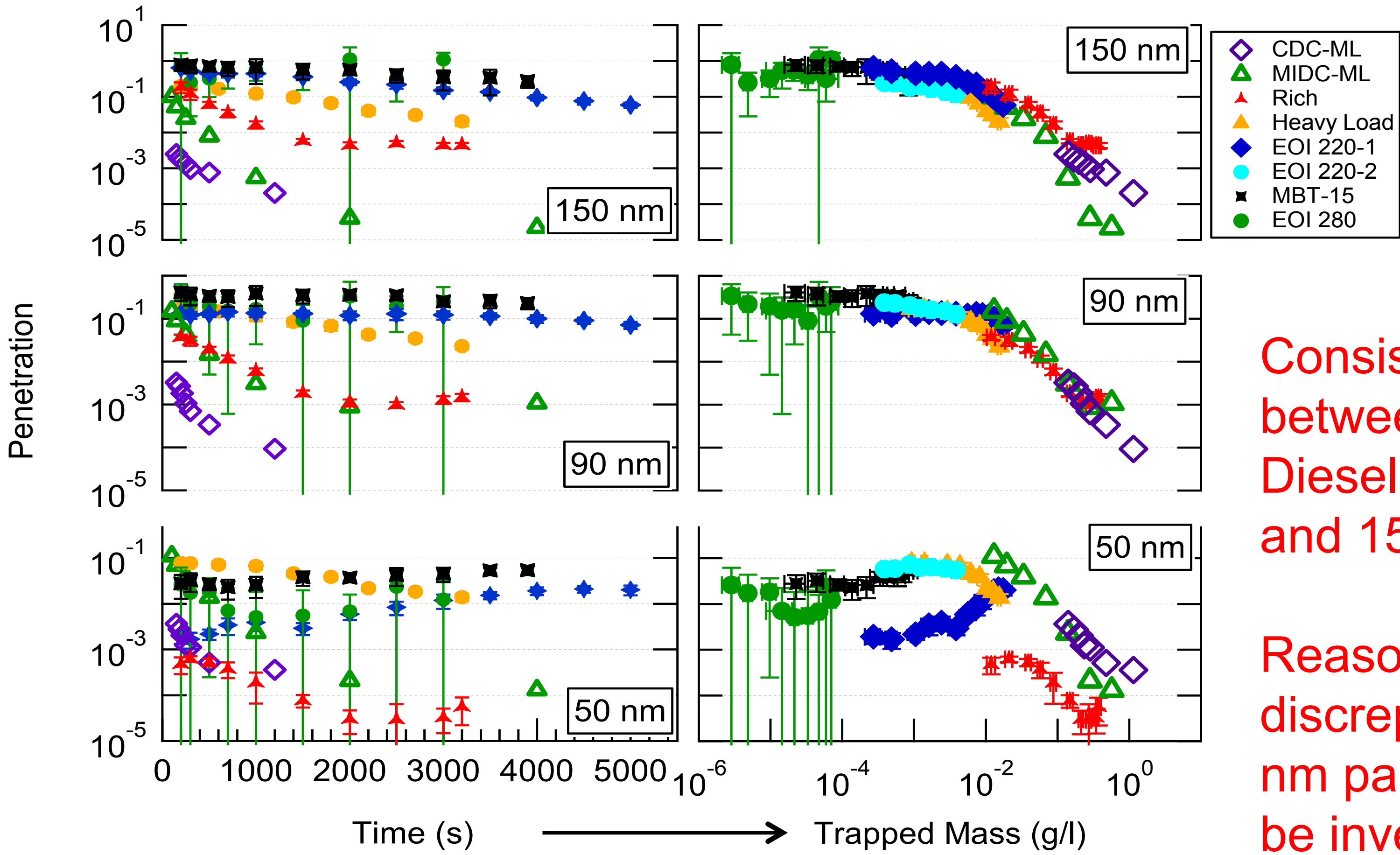


Fig. Evolution of particle penetration with loading time & trapped mass

Consistent overlap between SIDI & Diesel results for 90 and 150 nm particles

Reason behind discrepancy for 50 nm particle needs to be investigated further

Filtration Experiments

Normalized pressure drop (NPD)

■*Scaled@Pressre Drop = Pressure Drop/Filtration Velocity*

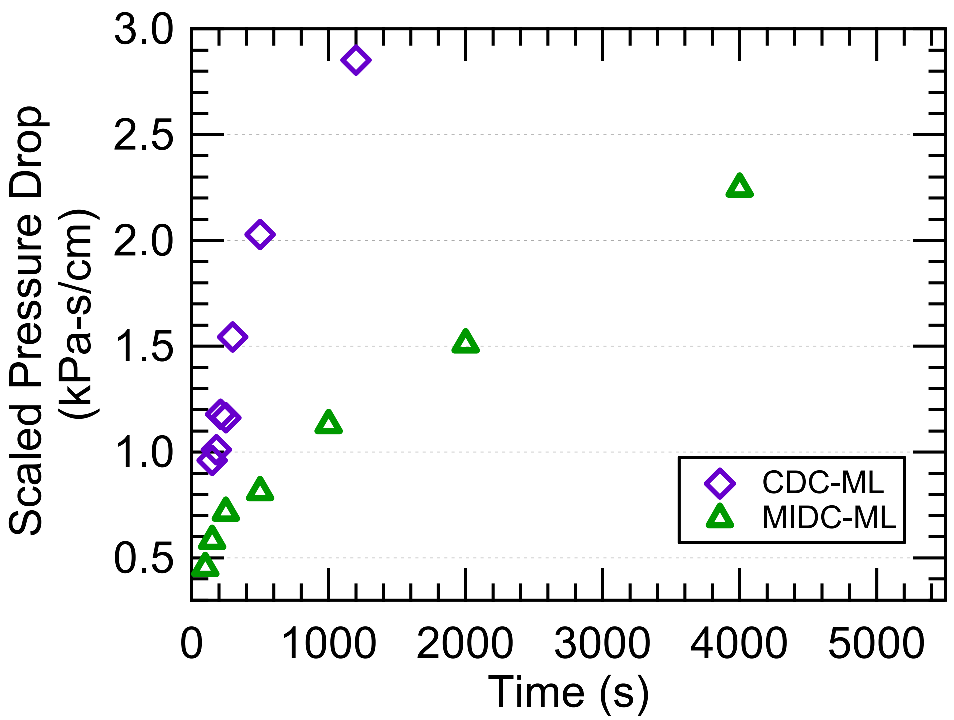


Fig. Evolution of scaled pressure drop with loading time

- Pressure drop was scaled to account for small changes in filtration velocity
- Holder effect was 0.11±0.1 (kPa-s/cm)
- HDD → Clear distinction between wall loading and cake build up regions

Filtration Experiments

Normalized pressure drop (NPD)

■*Scaled@Pressre Drop = Pressure Drop/Filtration Velocity*

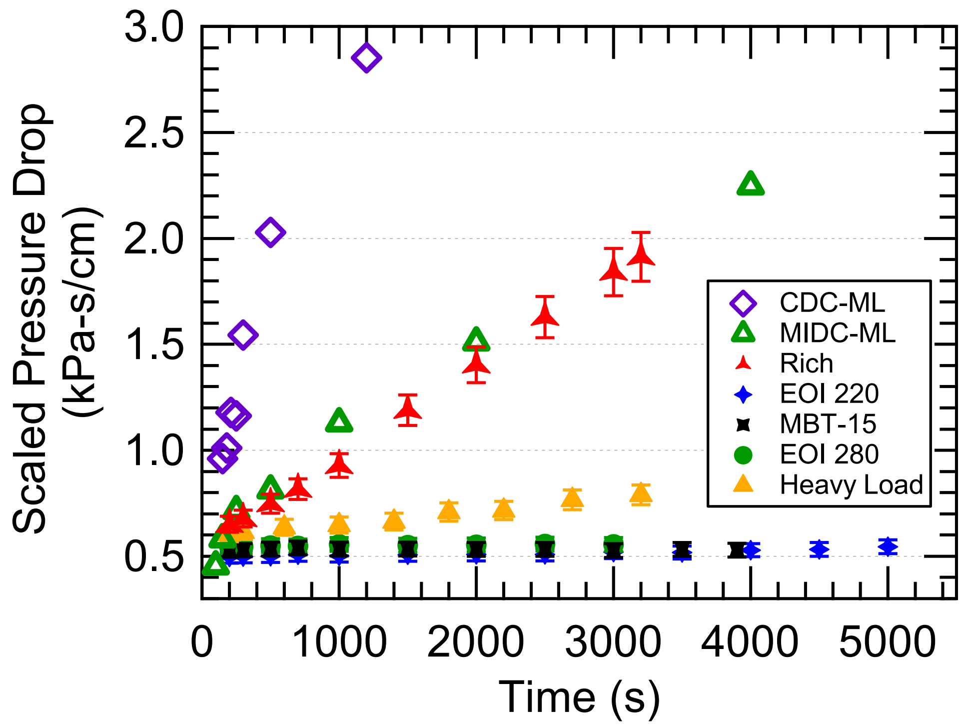
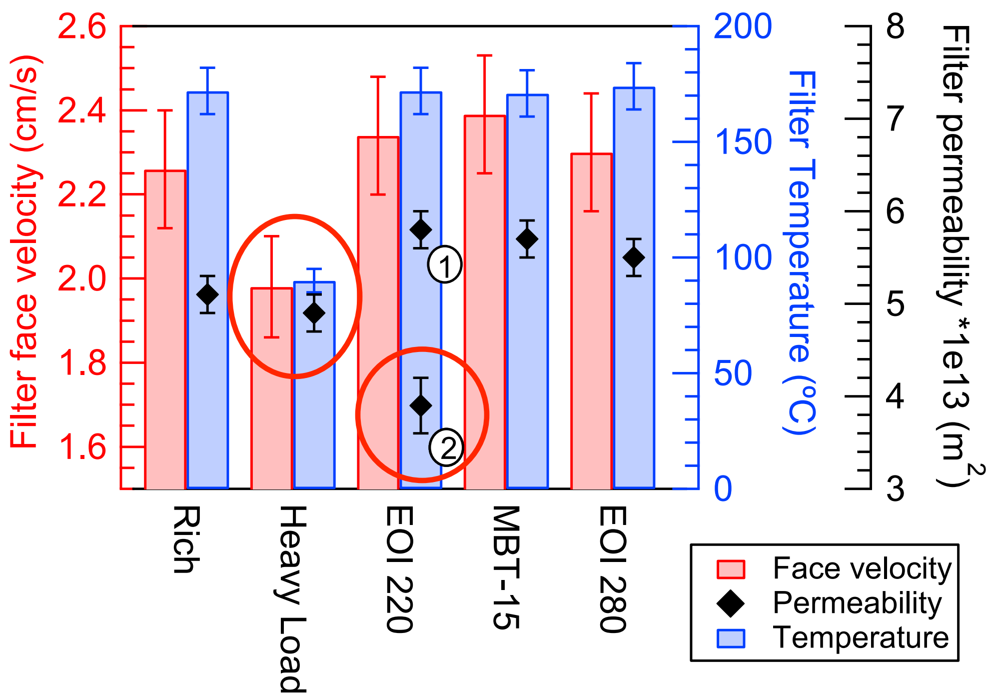


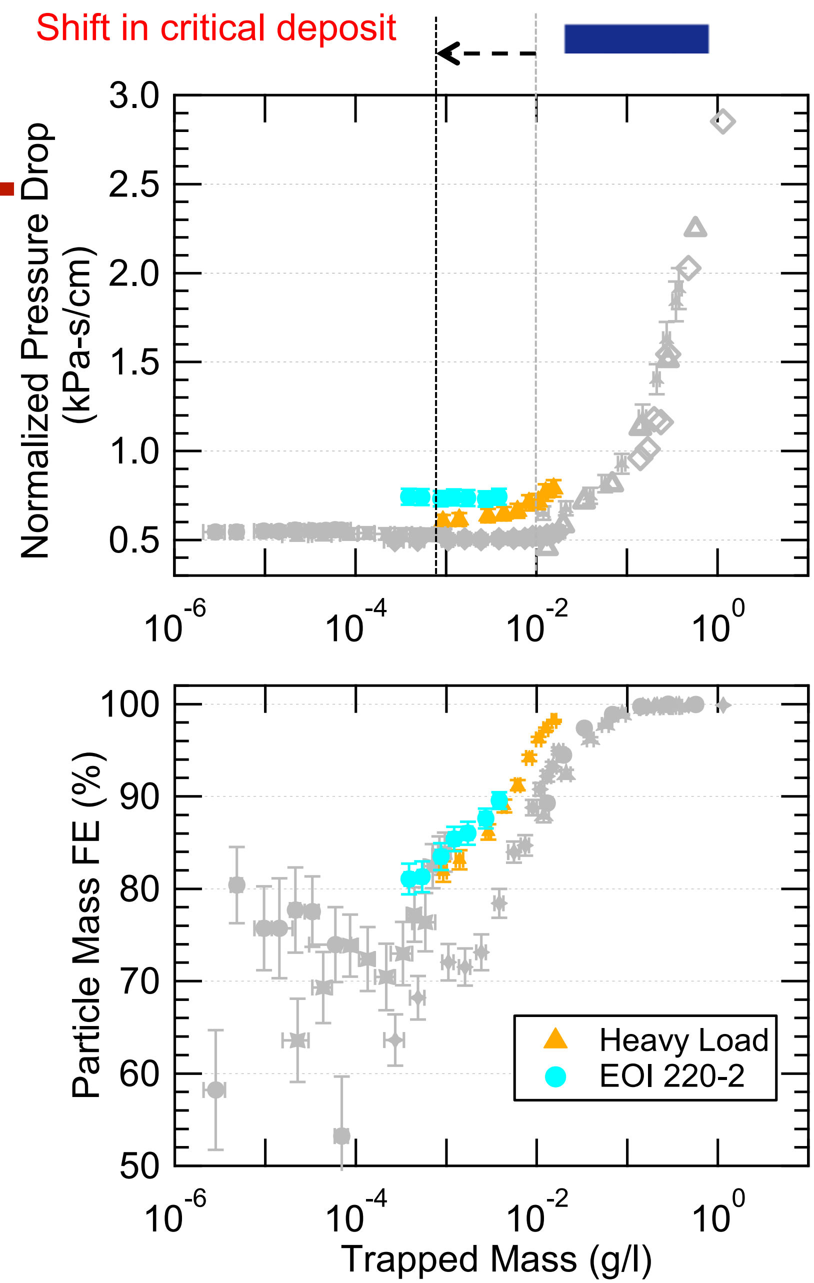
Fig. Evolution of scaled pressure drop with loading time

- Pressure drop was scaled to account for small changes in filtration velocity
- Holder effect was 0.11±0.1 (kPa-s/cm)
- HDD → Clear distinction between wall loading and cake build up regions
- SIDI → Only the Rich & HL conditions showed increase in NPD
- No distinct transition from wall loading to cake buildup observed for the Rich case

Filtration Experiments

Outliers





- HL and EOI 220-2 were outliers
- Possible shift in critical deposit observed
- Method shows sensitivity to experimental conditions and sample variability