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Particulate Emissions Control by Advanced Filtration Systems for GDI Engines

(ANL/Corning/Hyundai CRADA)

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DOE Annual Merit Review & Peer Evaluation Meeting

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Office of Vehicle Technologies

Project ID: ACE024

Overview

Timeline

- Start: Oct. 2011
  - Contract signed: Sept. 2012
- 10% Finished

Budget

- Funding received in FY12
  - DOE: $500K
  - Corning: $300K (in-kind)
  - Hyundai: $110K (in-kind) &
    $90K (fund-in)

Barriers

- Increased back pressure and fuel penalty
- Lack of effective regeneration strategies to reduce input energy
- Underdevelopment of filter materials for GDI PM emissions
- Insufficient information about GDI engine PM emissions

Partners

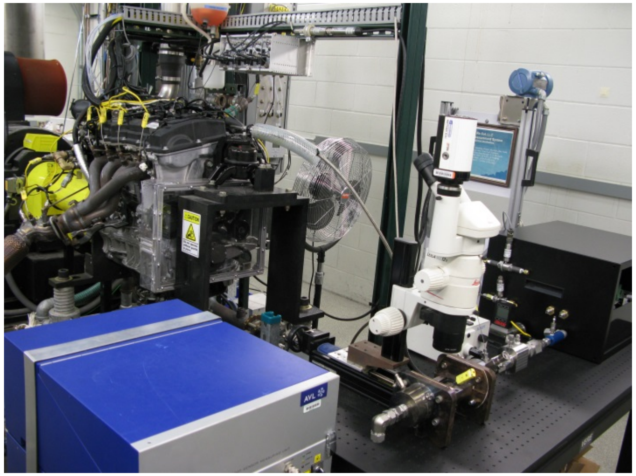
- Corning and Hyundai Motor
- University of Wisconsin – Madison
- MIT
- Tokyo Institute of Technology

Relevance and Objectives

- PM emissions are a major problem of GDI engines, but the filtration system (GPF) has not been developed yet.
- GPF system needs to be designed with care, because GDI engines operating at stoichiometric conditions are very sensitive to back pressure.
- Low back-pressure filters are needed to be developed.
- The properties of PM emissions from GDI engines have not been characterized yet.

- Evaluate the DPF filtration/regeneration performance as a function of flow condition and porosity.
- Evaluate the level of gaseous emissions and back pressure effects on engine performance to determine the GPF installation position.
- Characterize filtration process for different filter models along with measurement of pressure drop
- Characterize physical properties of PM emissions from a GDI engine.
- Conduct numerical modeling for soot loading in a GPF.

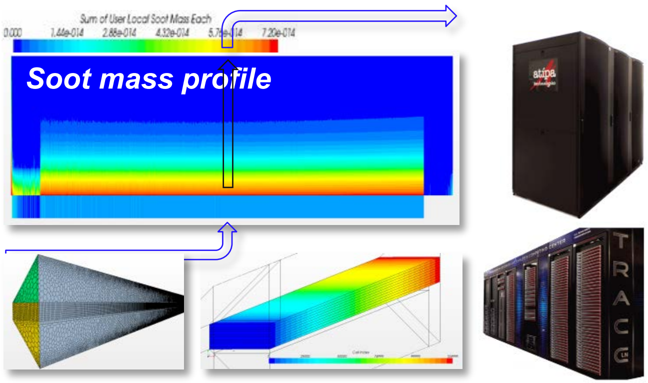
Approach



GPF experiments for filtration/ Regeneration with *μ*-imaging

Soot oxidation experiments with TGA, DSC, ESEM

2.4L GDI Engine

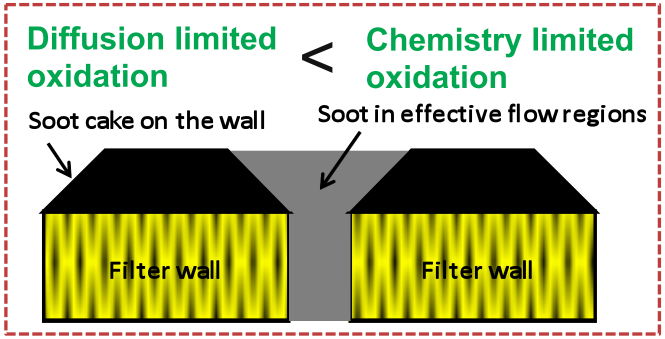


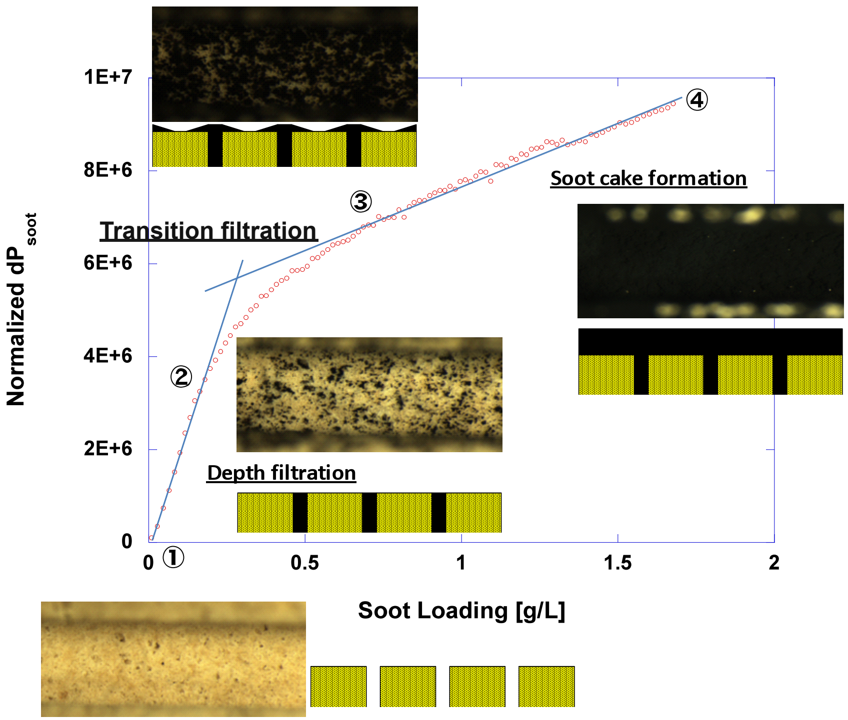
Numerical modeling

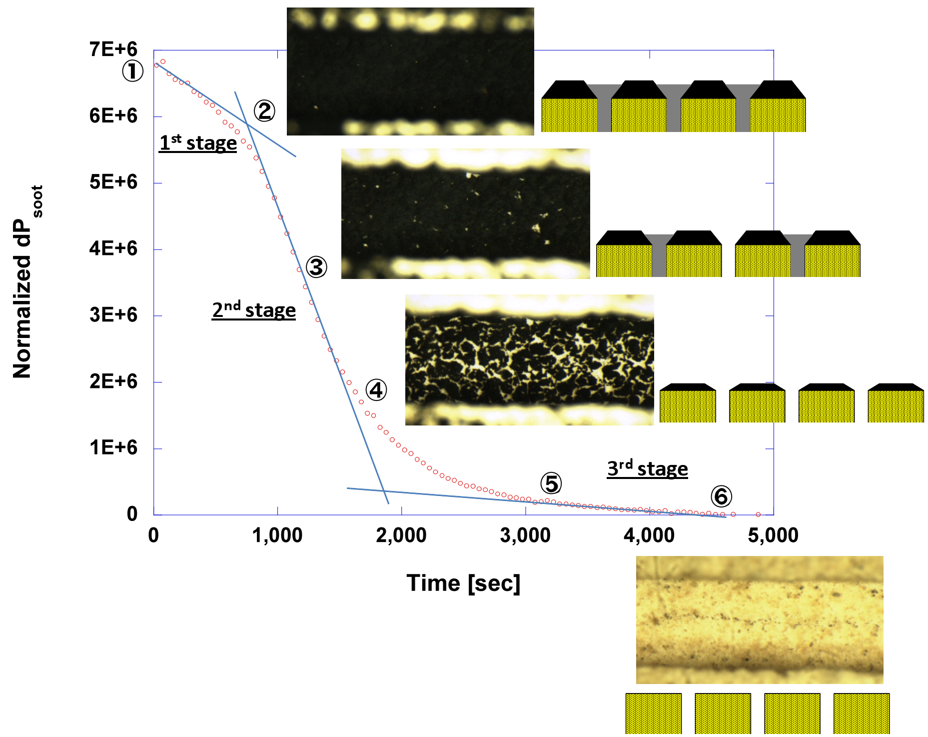
X-Ray measurement of soot

Microscopic visualization further offers understanding of soot filtration and regeneration behaviors in DPFs

- Pressure drop becomes most significant in the 2nd regeneration stage: soot oxidation enhanced in effective flow regions, where surface pores open.
- Soot deposited in pores and effective flow regions oxidizes faster than soot cake on the walls.



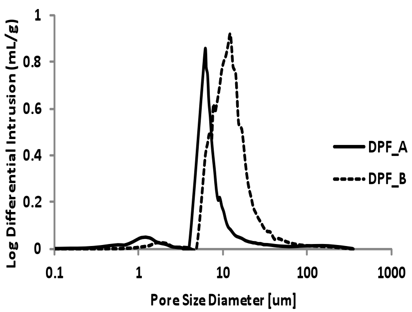




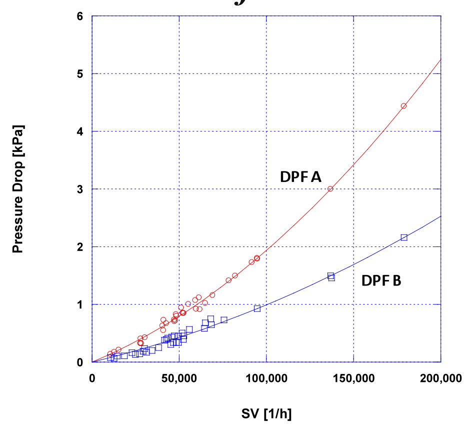
Experiments were conducted to find the effects of filter structure and emissions flow conditions on pressure drop in filtration

- Filter structure (porosity)

Pore size distribution



Clean filter ΔP



Description	DPF A	DPF B
Size	1.7” square x 6”	1.7” square x 6”
Cell density [cpsi]	200	200
Wall thickness [in]	0.012	0.012
Porosity (effective) [%]	**20.89**	**47.05**
Mean pore size (d_{50}) [μm]	7.242	11.948
Pore size distribution ((d_{50}-d_{10})/d_{50})	0.79	0.41
d_{10} [μm]	1.51	7.03
d_{90} [μm]	21.13	25.11

- Flow conditions (*Pe* #)

Low flow: 1500rpm - 4bar
High flow: 2500rpm - 6bar
for 2L diesel

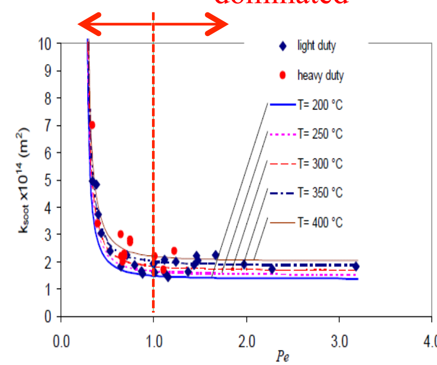
Convection

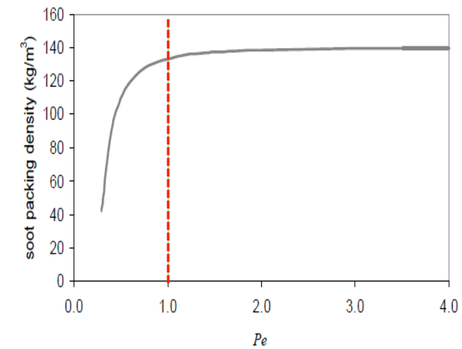
$$Pe = \frac{u_w \cdot d_{primary}}{D_p}$$

Diffusion

Diffusion dominated

Convection dominated

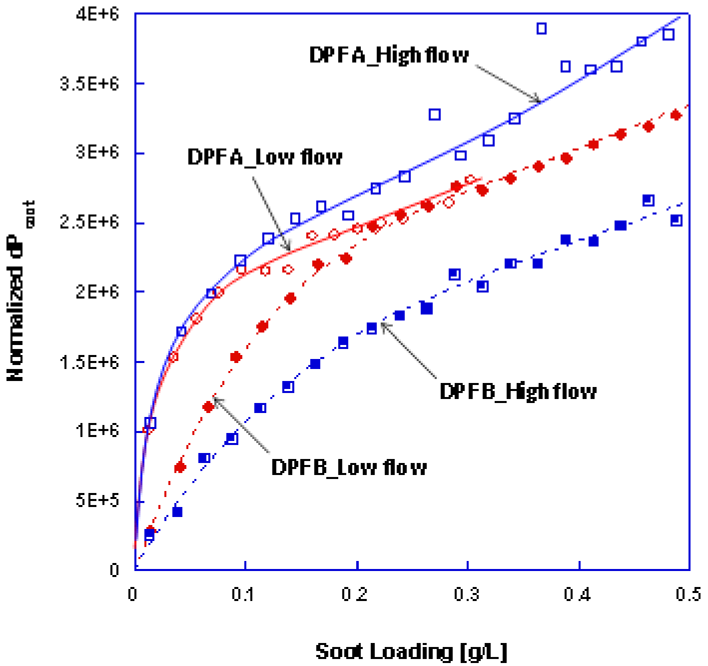




Pe asymptote (*Konstandopoulos*, SAE 2002-01-1015)

	U_{wall} (cm/s)	Pe_{wall}	U_{pore} (cm/s)	Pe_{pore}
DPF A_Lowflow	0.777	**0.236**	3.719	**1.131**
DPF A_Highflow	2.212	**0.672**	10.587	**3.219**
DPF B_Lowflow	0.892	**0.271**	1.894	**0.576**
DPF B_Highflow	2.233	**0.679**	4.745	**1.442**

Pressure drop by soot depends on flow conditions (Pe) and the results propose optimal filter design



Pressure drop (ΔP_{soot}) during depth filtration

- **High porosity filter** < Low porosity filter
- **No significant difference between convection-dom flows (DPF A).**
- **Convection-dom flow (Pe_{pore} >1)** < Diffusion-dom flow (Pe_{pore} <1) **(DPF B)**

Pressure drop (ΔP_{soot}) during soot cake formation

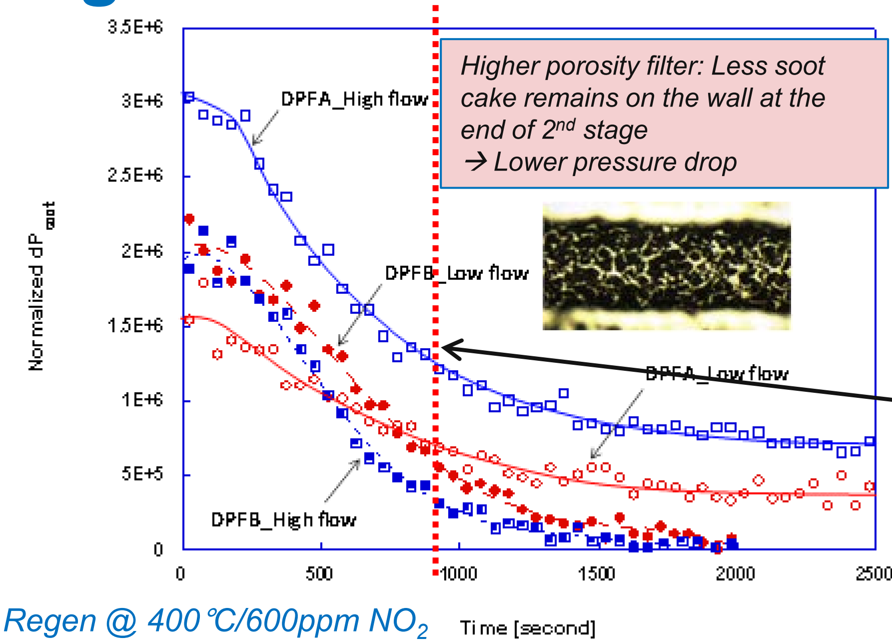
- No consistent correlation between porosity and ΔP_{soot}
- ΔP_{soot} correlation found with Pe_{pore}, but not Pe_{wall}: because local flows in the 'effective flow region" indeed affect the pressure drop.
- An **optimal Pe_{pore}** is about **unity (1).**

Optimal flow condition to minimize pressure drop in the entire filtration period

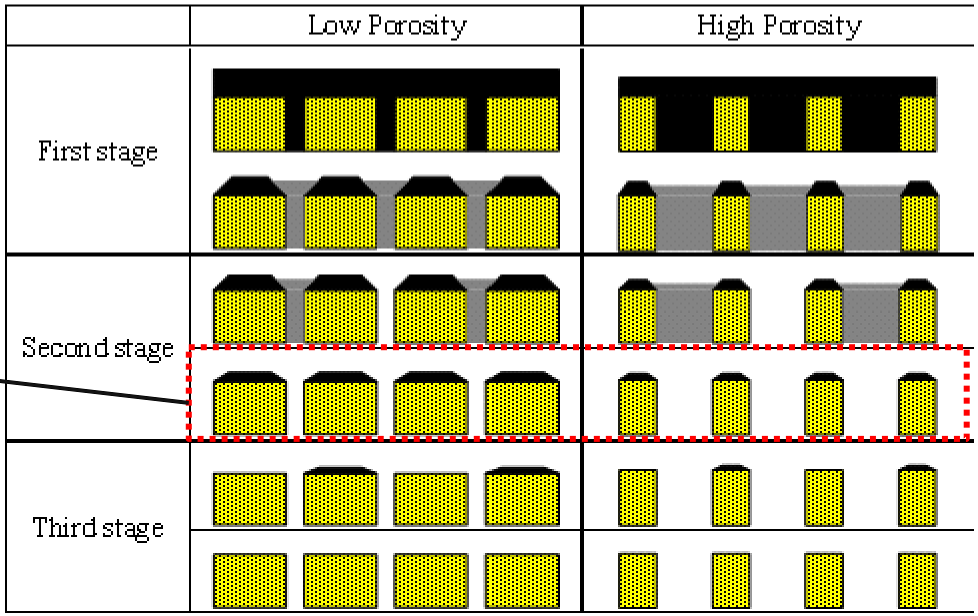
- **Pe_{pore} greater than unity** (for depth filtration), but as **close to unity** as possible (for soot cake filtration).
- Filter geometry needs to be designed to meet the **optimal Pe_{pore}** condition.

	DPF A Lowflow	DPF A Highflow	DPF B Lowflow	DPF B Highflow
Pe_{wall}	0.236	0.672	0.271	0.679
Pe_{pore}	1.131	3.219	0.576	1.442
Total soot loading [g/L]	0.313	0.631	0.540	0.598
Soot loading during depth filtration [g/L]	0.034	0.033	0.118	0.163
Gradient of ΔP profile in depth filtration [Norm. ΔP_{soot}/(g/L)]	43,796,817	42,837,006	18,372,021	10,518,552
Gradient of ΔP profile in soot cake formation [Norm. ΔP_{soot}/(g/L)]	2,755,172	4,772,154	3,079,911	2,595,161

High porosity filter decreases back-pressure in regeneration and increases regeneration efficiency



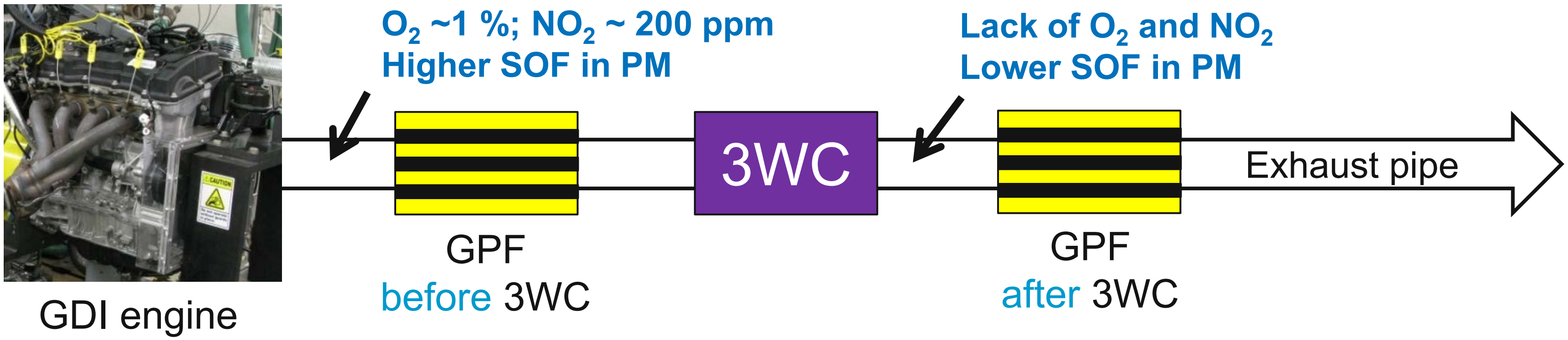
Regen @ 400℃/600ppm NO_2



- ***Regeneration may need to stop at the end of 2nd stage,*** because the following slow pressure recovery (diffusion-limited) may increase energy consumption.
- ***Regeneration time to the end of 2nd stage is quite constant,*** independent of soot loading conditions (*Pe*) and filter physical properties.
  - ***Pressure drop rate** = f(total soot loading mass)*
    ***Regeneration efficiency** = f(filter porosity)*
- ***Higher porosity filter offers better pressure drop recovery and higher regeneration efficiency.***

	DPF A Lowflow	DPF A Highflow	DPF B Lowflow	DPF B Highflow
Total soot loading (g/L)	0.313	0.631	0.540	0.598
Required time to the end of 2nd stage (sec)	1,129	1,013	1,104	864
ΔP drop rate in 2nd stage (Norm. ΔP_{soot}/sec)	-1,064	-2,141	-2,148	-2,611
ΔP_{soot} at end of 2nd stage (Regeneration efficiency)	423,182 (71.8%)	827,054 (71.5%)	294,481 (85.8%)	166,154 (91.5%)

GPF systems have technical questions to be resolved

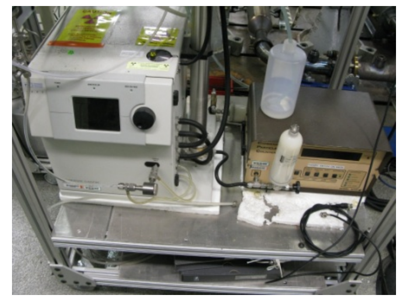


	before 3WC	after 3WC
Pros	• Existence of $\mathbf{O_2}$ and $\mathbf{NO_2}$ and **high temperature** enable continuous regeneration	• **Lower back pressure**
Cons	• **Longer 3WC heat-up time** needed • **Higher back pressure**	• **Insufficient oxidizers** for regeneration
Questions	• Proposal of **GPF specs** suitable for the acceptable pressure-drop limit? • Possibility of **continuous regeneration** and **balanced pressure drop**?	• Regen strategy – engine **fuel-cut** operation is enough for regeneration, or periodic **lean operation** is required? • **Effects of soot property changes** after 3WC on filtration and regeneration?

Hyundai 2.4L GDI engine installation has been completed on a 150 hp AC dynamometer

- Hyundai 2.4L Theta II GDI engine and emissions measurement instruments

Rated power: 148 kW @ 6,300 rpm
Rated torque: 250 Nm @ 4,250 rpm



<SMPS & CPC>

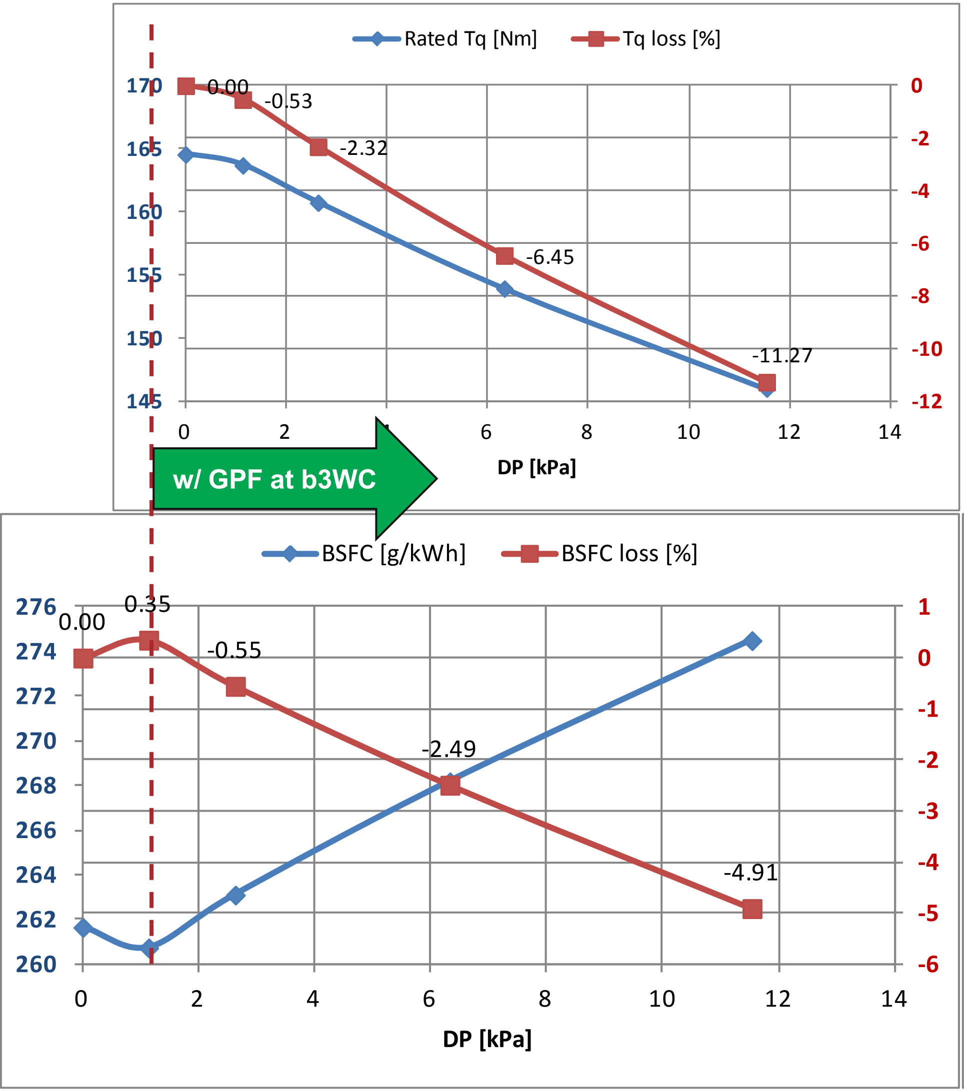
<Micro Soot Sensor>

<Emission bench>

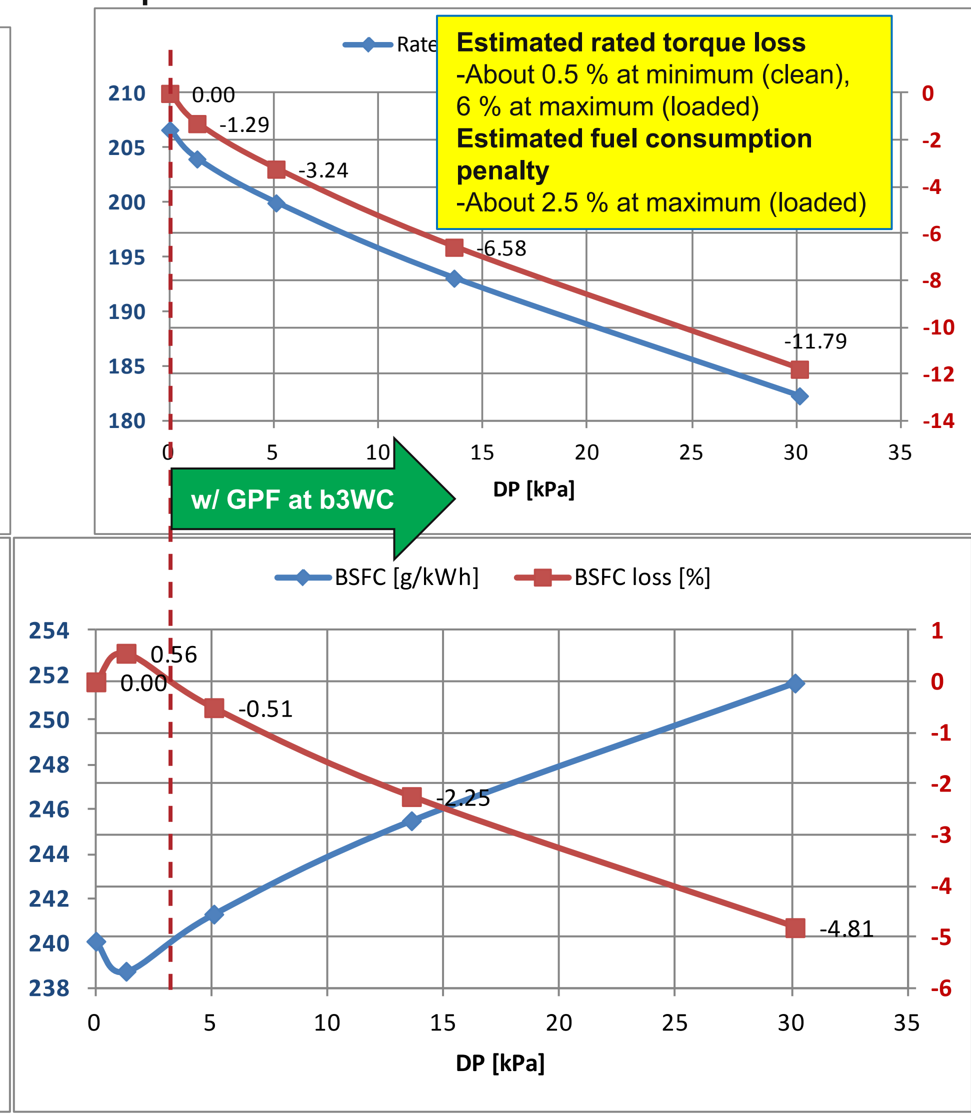
<TEOM>

Engine performance was evaluated for the case of virtual installation of a GPF b3WC: Torque loss and fuel consumption penalty due to P_{back}

<1500 rpm>

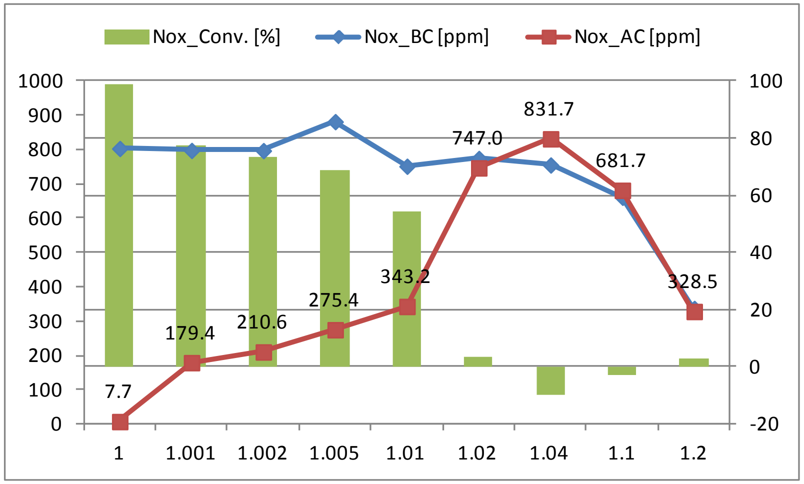


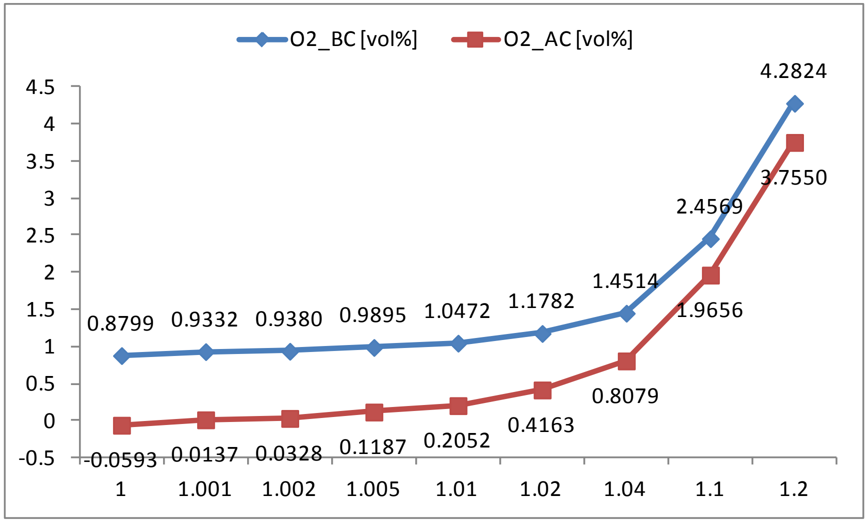
<3000 rpm>

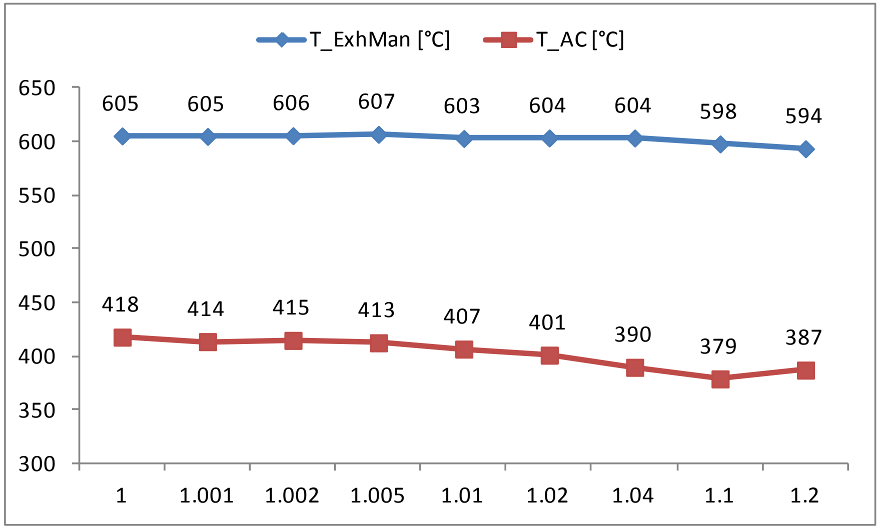


Changes in oxidizer concentrations at lean-burn conditions were evaluated for GPF regeneration after 3WC

- 1600 rpm / 2.4 bar BMEP
  - Lean-burn operation enhanced O_2 concentration, but deteriorated the NO_x conversion: 0.1%-O_2 vs. 70%-NO_x conversion
    - *Lean-burn operation may not be applicable to regeneration after 3WC due to the NO_x penalty.*
  - Exhaust temperature cooled down to about 400˚C.
  - Therefore, fuel-cut effects will be evaluated.

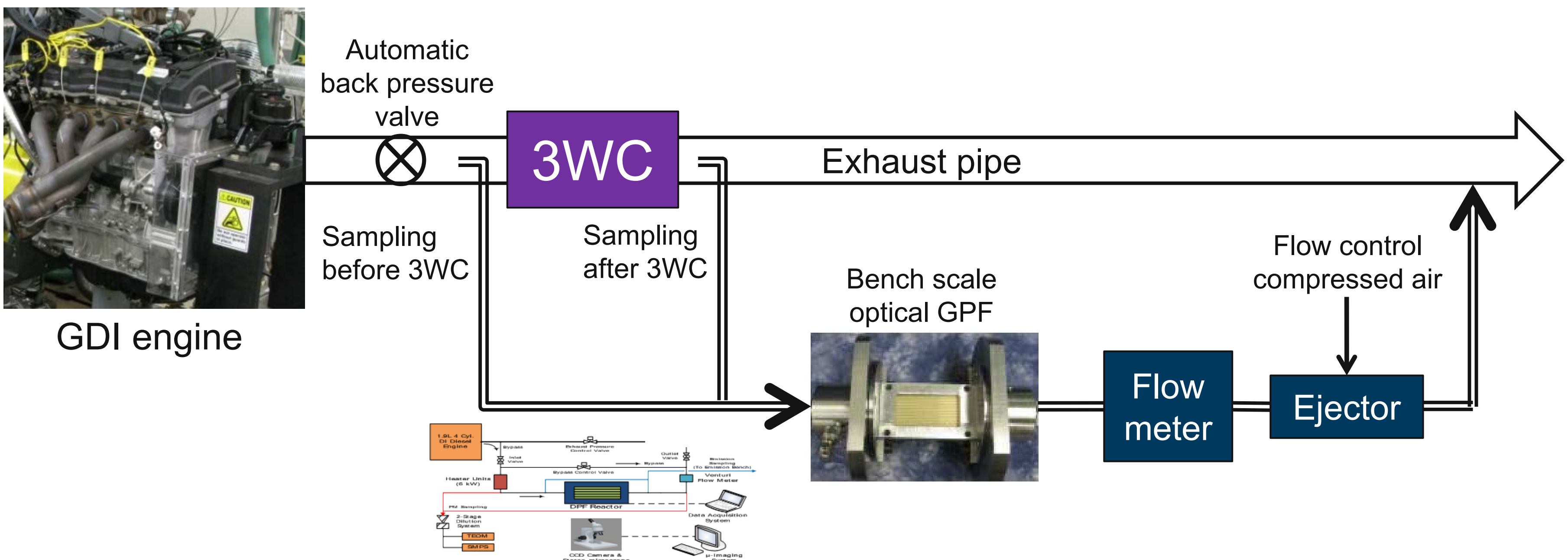




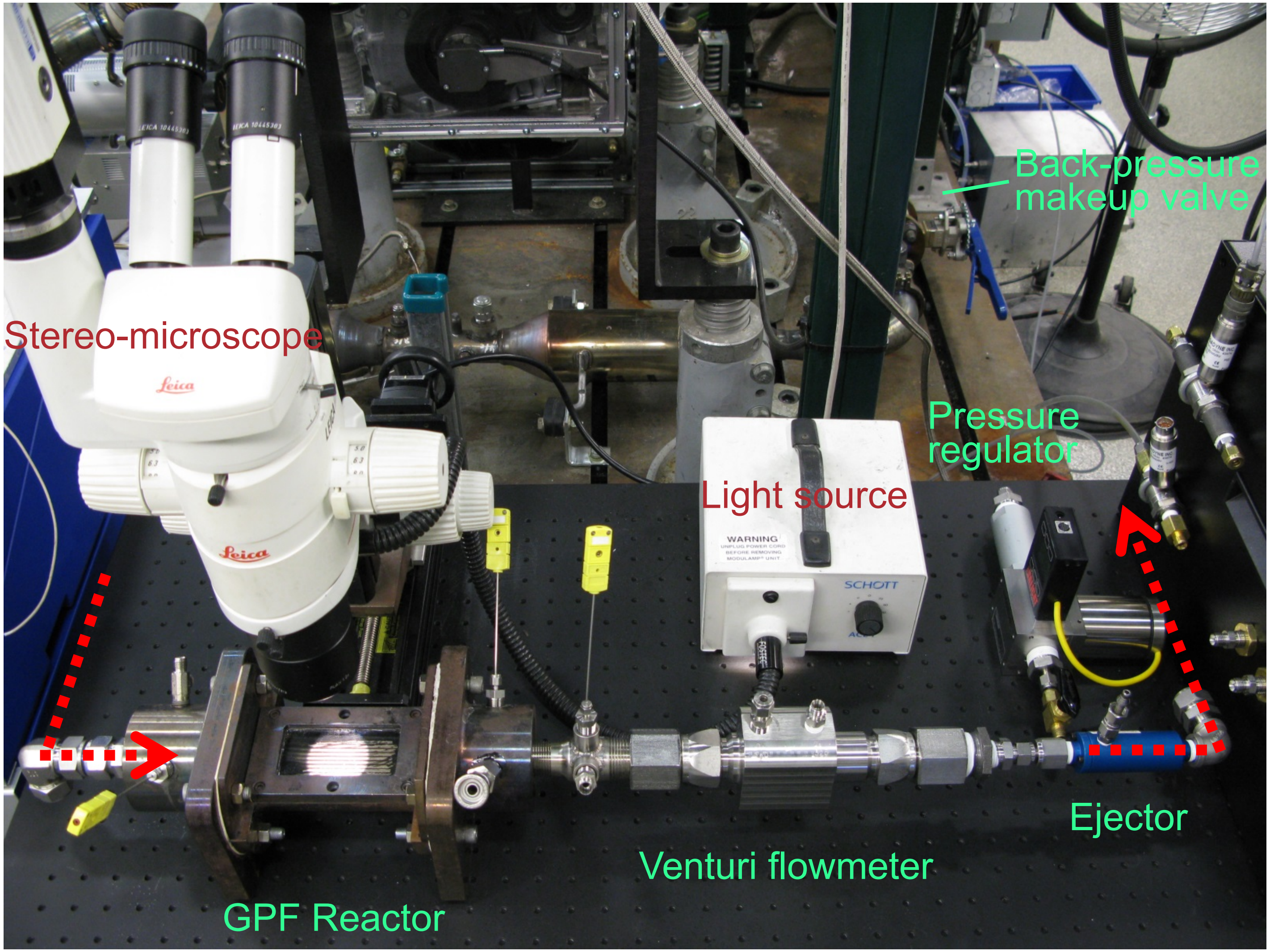


The test bench was fabricated with automatic engine exhaust back-pressure and sample flowrate control systems

- Bench-scaled (2” x 6” bisected) optical GPF test system
  - Engine back-pressure and emissions flowrate are automatically controlled to simulate practical GPF system.
  - Microscopic processes of soot filtration/regeneration will be visualized in filter channels, along with pressure drop measurements.
  - Filtration/regeneration experiments will be conducted both before and after three-way catalyst (3WC)



A new GPF bench test system has been fabricated



In-situ observation of soot cake oxidation using E-SEM

- Microscopic observation of DPF regeneration
  - Soot cake layer deformation during oxidation
  - Soot-catalyst contact (e.g., loose or tight)

  → This work enables us to analyze oxidation behaviors of soot cake at a microscopic scale.

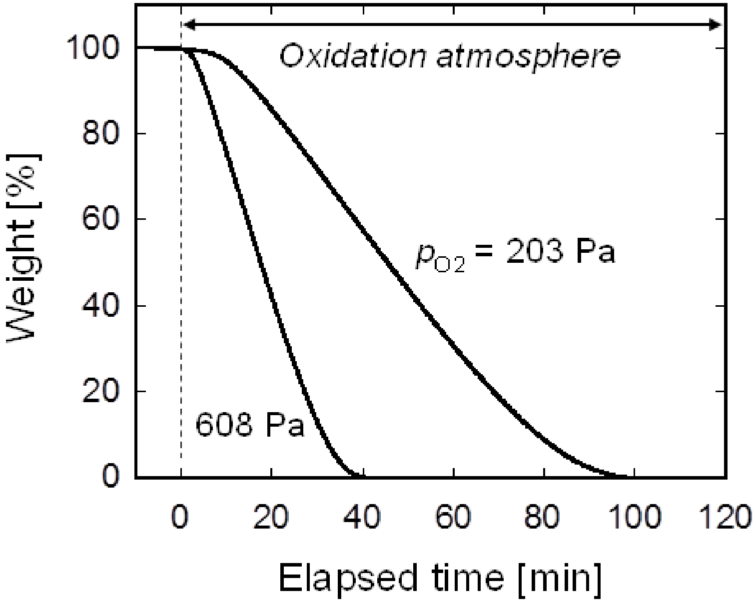
- Environmental Scanning Electron Microscope (E-SEM)
  - In-situ observation of soot oxidation at micro-scales
  - Chamber conditions
    - *Wide range of pressure change (vacuum to 2.6kPa)*
    - *Various reactant gases, such as air, oxygen*
    - *Temperature controllable up to T_{max} = 1500 ℃*
    - *Quasi-steady state in the chamber.*

E-SEM visualizes soot cake oxidation on a filter membrane at a real time

- Thermogravimetric analysis

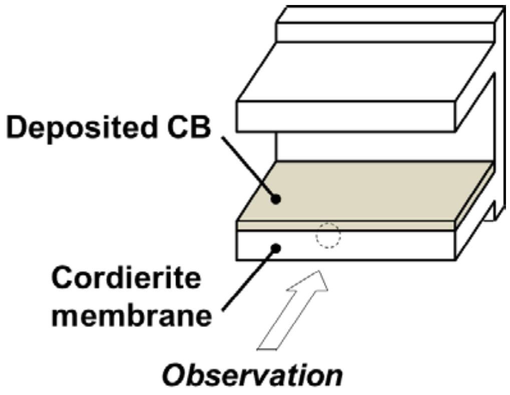
Isothermal analysis at 800°C

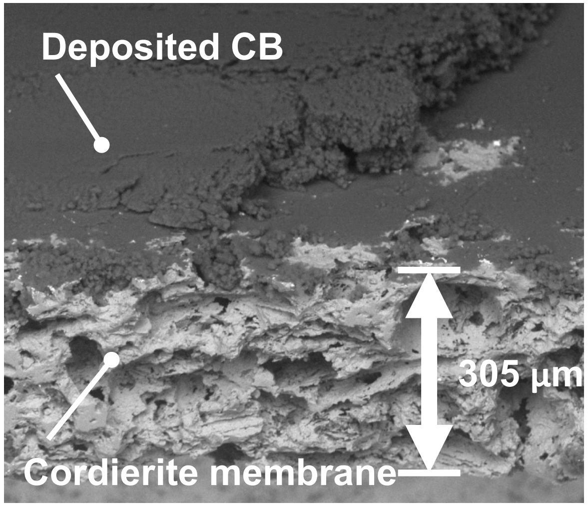
Surrogate soot (carbon black)

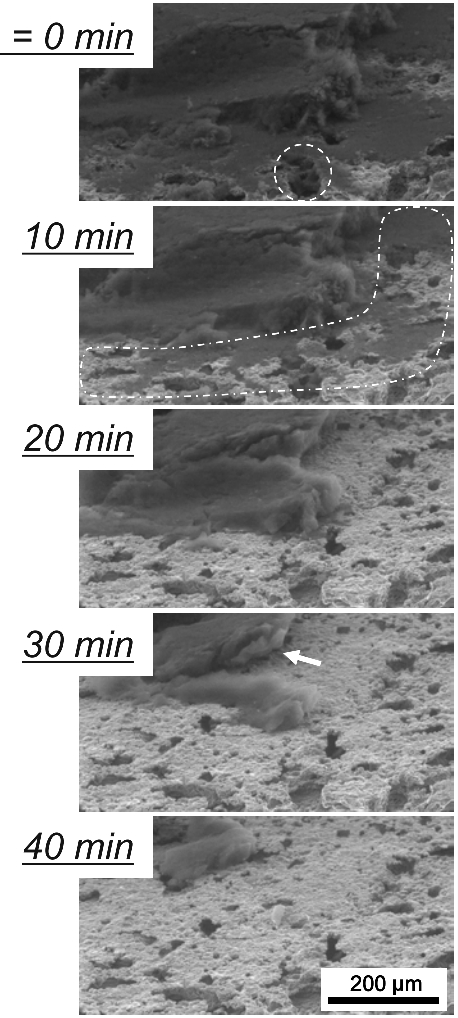


- To complete oxidation within 60 min, 4.0 Torr (533 Pa) of O_2 was used in ESEM experiments

- ESEM observation (800°C, 4.0 Torr O_2)



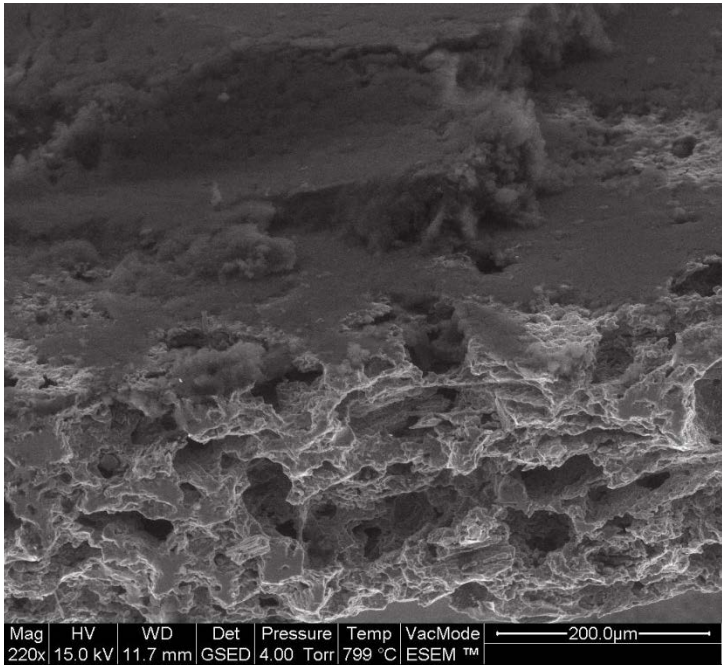




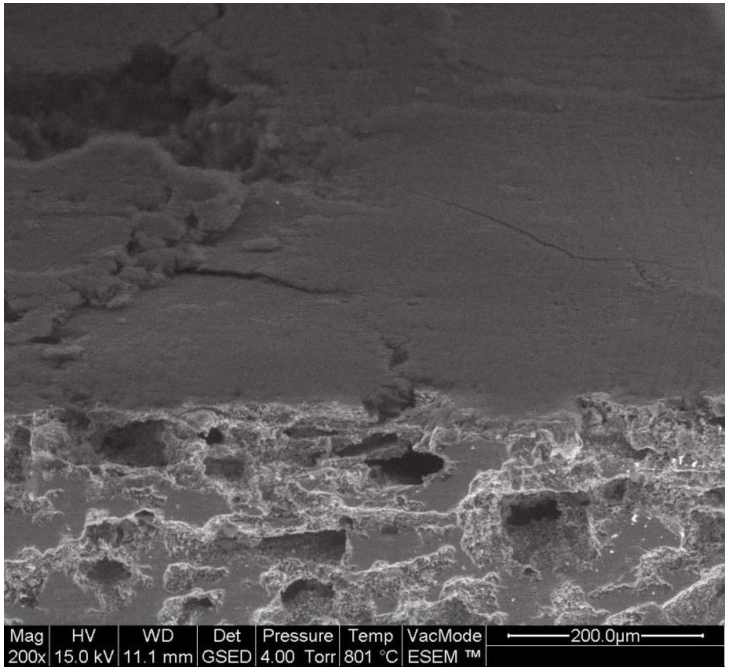
Catalyst coating on DPF demonstrates significantly different oxidation behaviors

Surrogate soot (carbon black), 800°C, 4.0 Torr of O_2

(1) Cordierite w/o catalyst

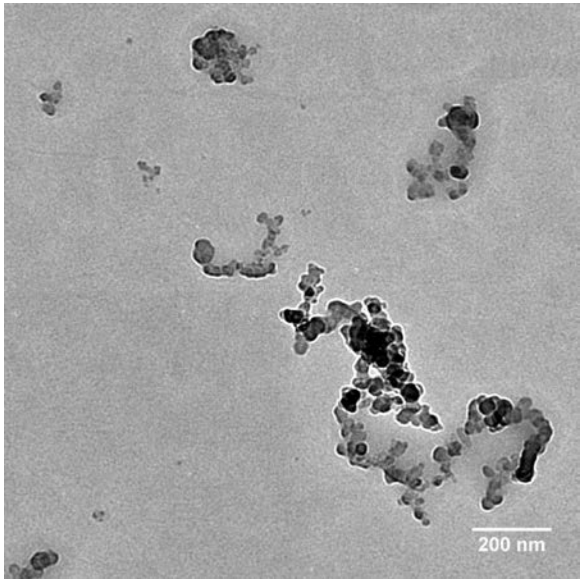


(2) Pt-catalyst coated

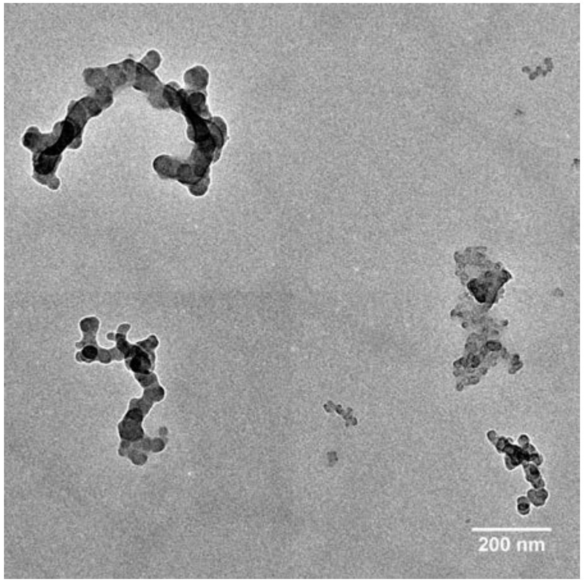


- (1) Relatively firm contact of soot cake with the substrate: Oxidation shrinks soot cake as a bulk solid material.
- (2) Loose contact of soot cake: The contact condition needs to be enhanced to utilize the catalytic effects.

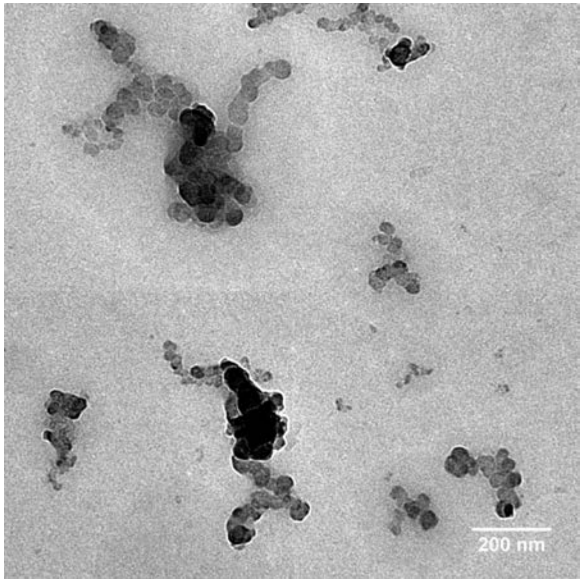
TEM revealed a wide range of particulate size from a GDI engine (collaboration with UW-ERC)



Gasoline, ø = 0.98, 310° bTDC



Gasoline, ø = 1.13, 310° bTDC

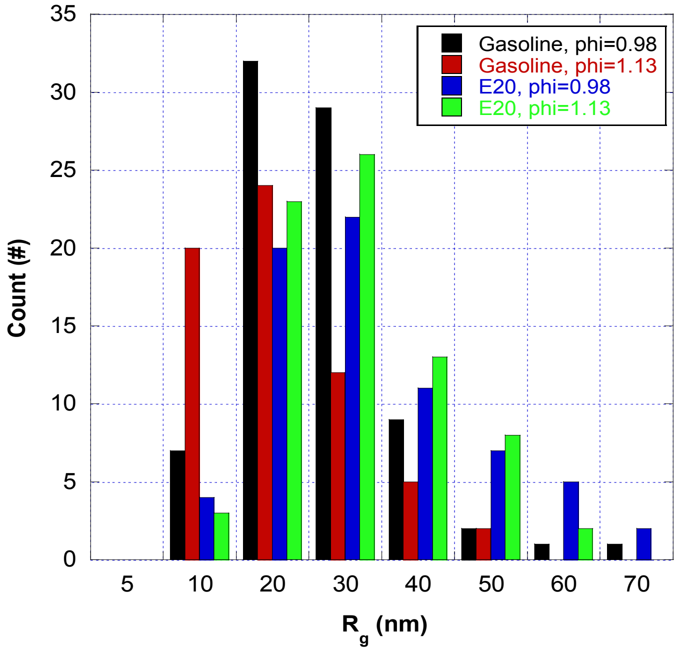


E20, ø = 0.98, 310° bTDC

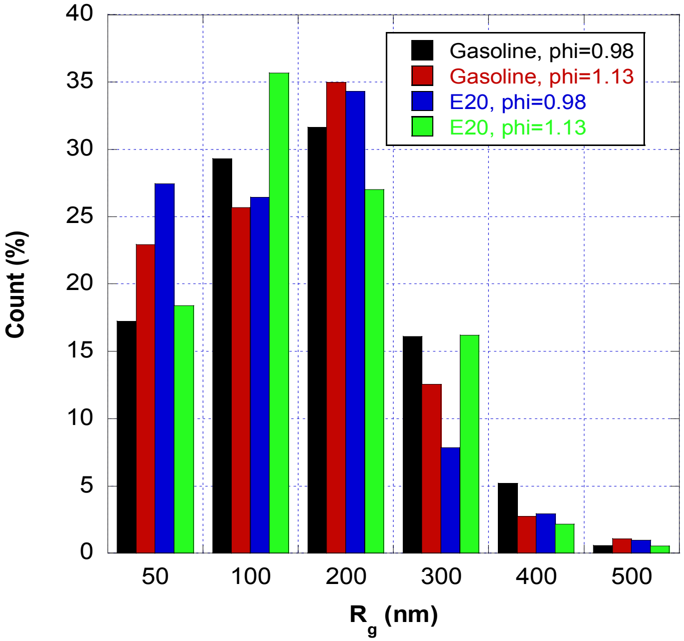
- 549 cc single-cylinder GDI engine; 2100 rpm/650 kPa IMEP; Inj. time: 220 – 310° bTDC
- Two different categories of particles were clearly observed:
  - Aggregates of small primary particles (d_p = 5-10 nm)
  - Aggregates of large primary particles (d_p = 20-50 nm).
- Single nanoparticles were found to be smaller than 10 nm in diameter.

Detailed image analysis revealed two distinct particle size distributions (at 310° bTDC)

❖ Aggregates of small primary particles



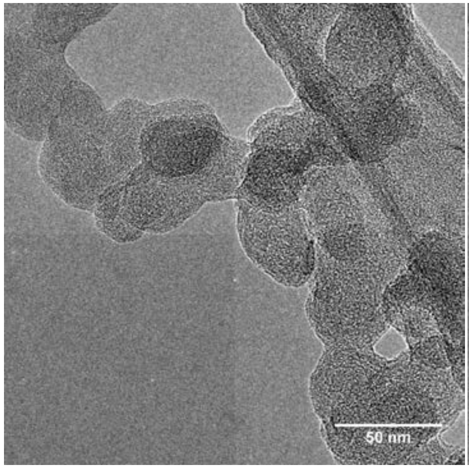
❖ Aggregates of larger primary particles



- Aggregates with small primary particles lies in a size range of R_g=5 to 70 nm, while those with large primary particles in a size range of R_g=25 to 500 nm.
- The advancement of fuel injection timing seems to be responsible for generating two different categories of particle sizes (e.g., fuel impingement)
  - Large aggregates with large d_p : contribution of hydrocarbons to soot growth.
  - Small aggregates with small d_p : inception of nascent soot particles.

GDI particles exhibited complexity in nanostructure

❖ E20, ø = 1.13, 280° bTDC



Initial image

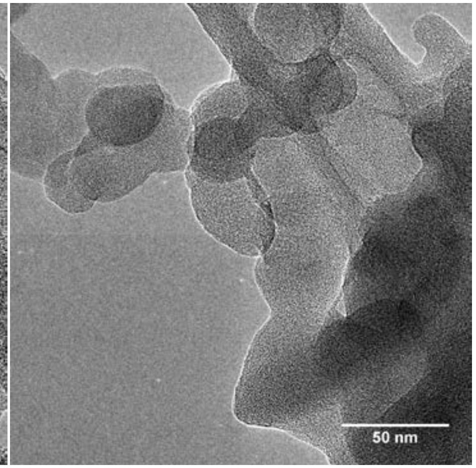


Image after 600kX

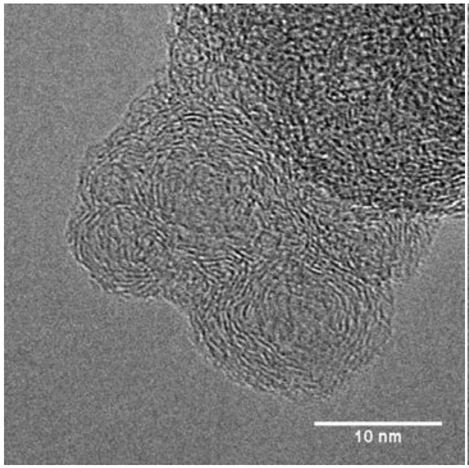


Image 1 at 600kX

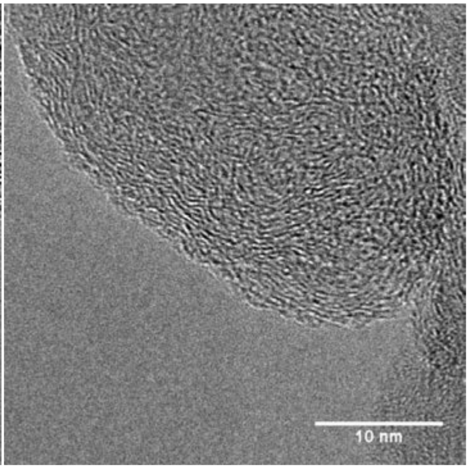
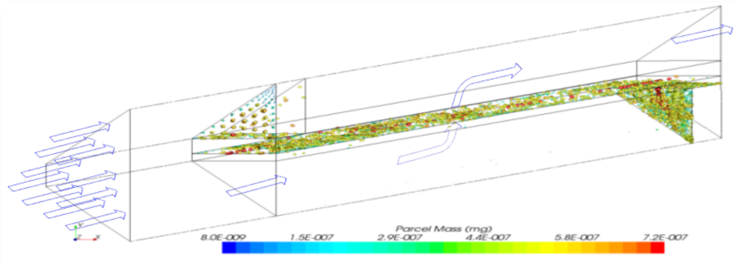


Image 2 at 600kX

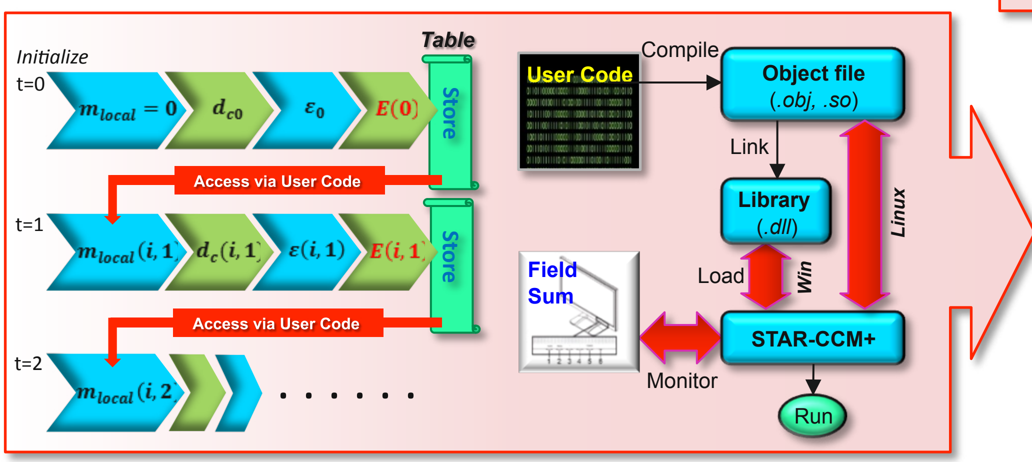
- Soot particles from E20 were often observed to expand and change the nanostructure at high magnifications (high electron energy), which has rarely been observed for diesel particles.
- Detailed examination on nanostructure revealed particles present at different levels of soot graphitization.
- Differences in nanostructures appeared to be insignificant with variations of fuel injection timing, fuel type and equivalence ratio.

Two different approaches were used for soot filtration modeling

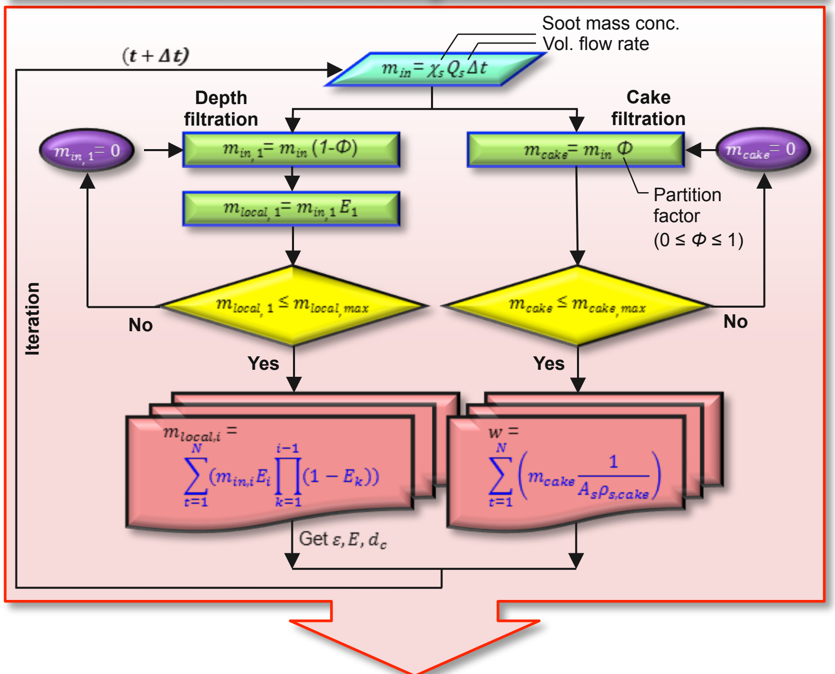
- **Lagrangian approach (FY11)**
  - Objectives: Qualitative analysis by tracking particles trajectories with appropriate B.C.s.

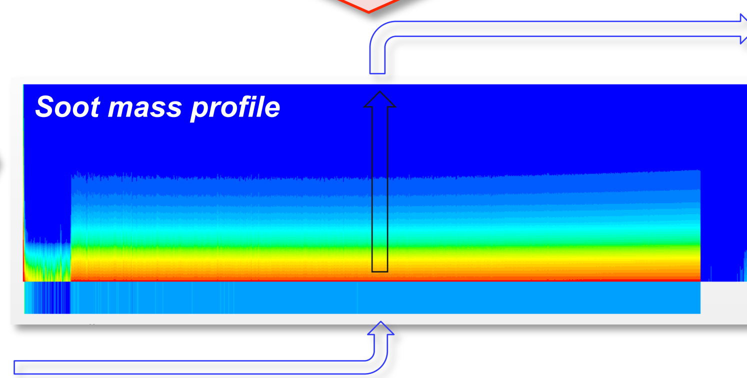


- **Eulerian approach (FY12)**
  - Objectives: Quantitative analysis of local values of filtration parameters by integrating user codes.



Numerical algorithm applied via self-developed user subroutines is integrated in the CFD code



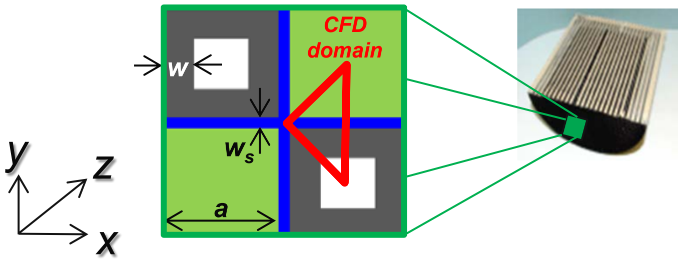


A 3-D CFD model has been developed for detailed numerical analysis of soot filtration processes

CFD domain setup

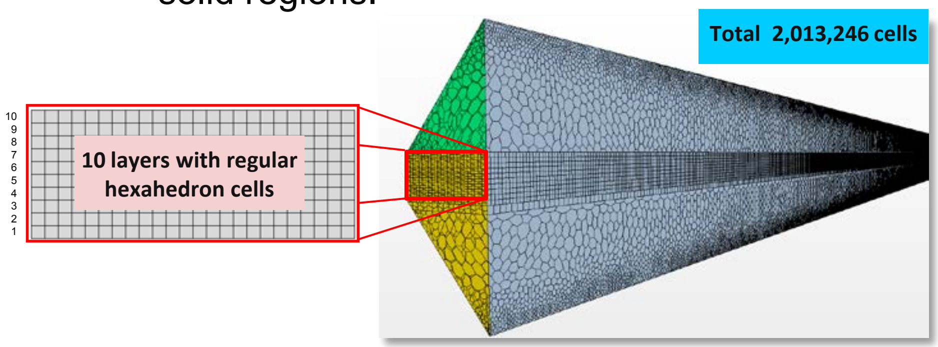
- Geometry: 200 cpsi, lab-scale (2”x 6”) cordierite filter with regions of upstream and soot cake.

*Upstream=**L** 0.78”, Plug= **L** 0.39”, w_s= 12.0 mils*



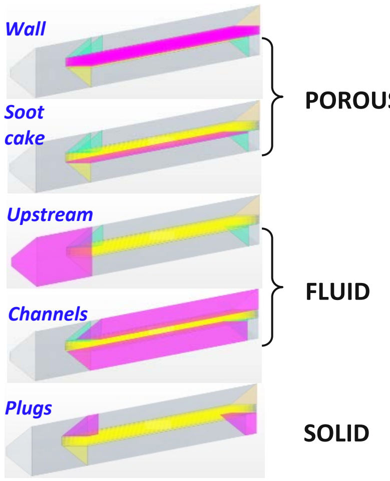
Meshing

- Volume meshes are generated by ***Trimmer*** for porous regions and ***Polyhedral*** for fluid and solid regions.



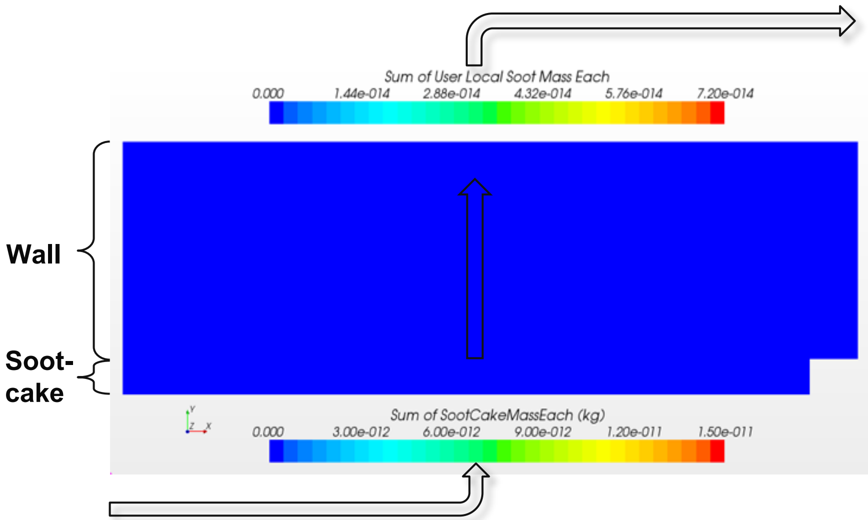
Physical assumptions for model setup

1. Fluid: 3D, Ideal gas, Laminar, Incompressible
2. Implicit unsteady (2nd order temporal discretization)
3. Segregated flow solver (2nd order convection scheme, URF= 0.5***P***, 0.2***V***)
4. Convective heat loss
5. No flow in axial(z) direction in wall regions
6. PM is homogeneously distributed in the flow
7. PM properties (d_p=54.5 [nm], ρ_p=2.87 [g/cm^3]) are estimated from experiments

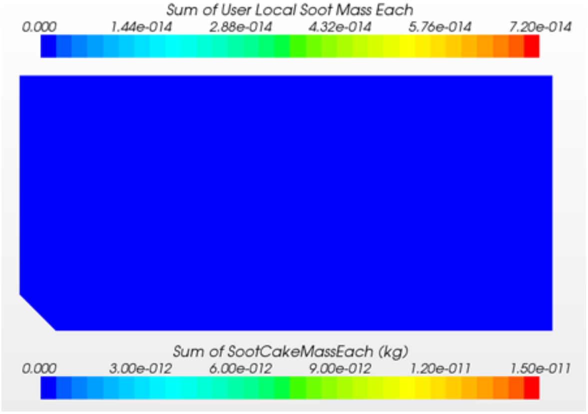


Modeling Results (Simulation duration: 35 min)

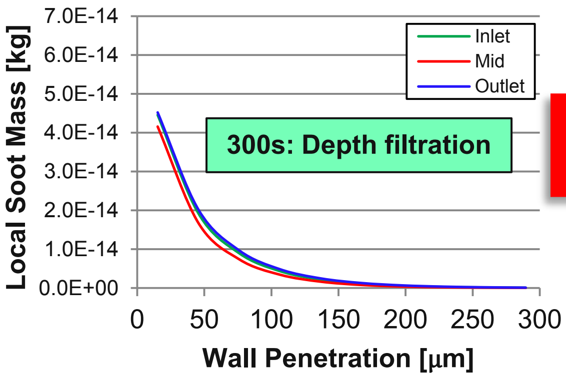
- **Temporal evolution of local soot mass**
  - y-z plane view (@ x = 1/4a)

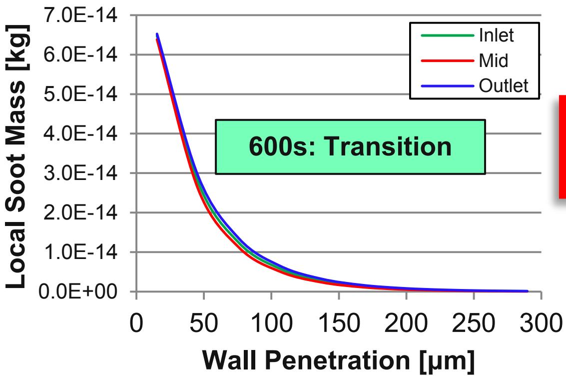


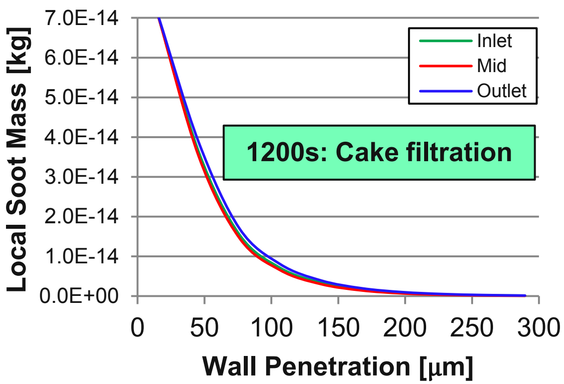
  - x-y plane view (@ z = 1/2L)



  - Deposited soot profiles



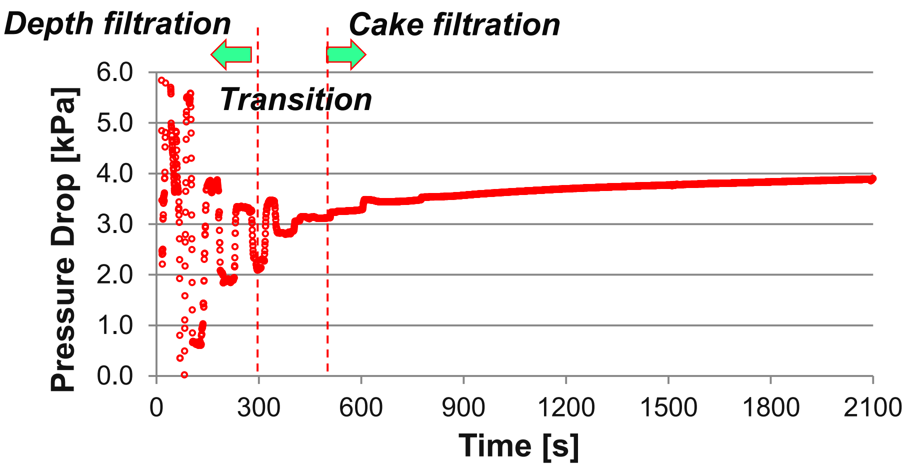




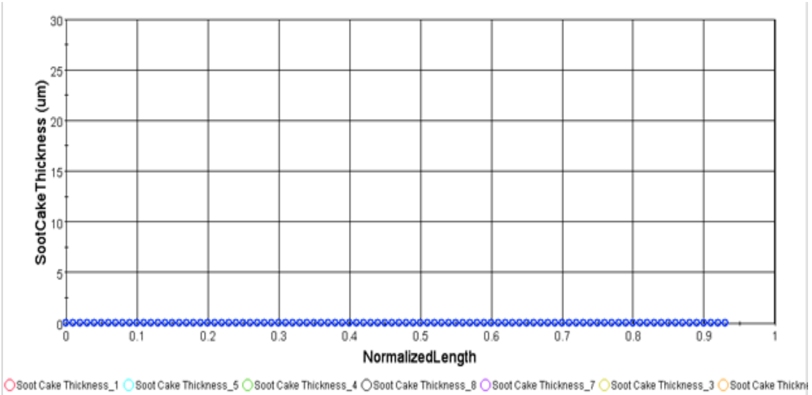
Modeling Results (Simulation duration: 35 min)

Temporal evolution of the other filtration parameters

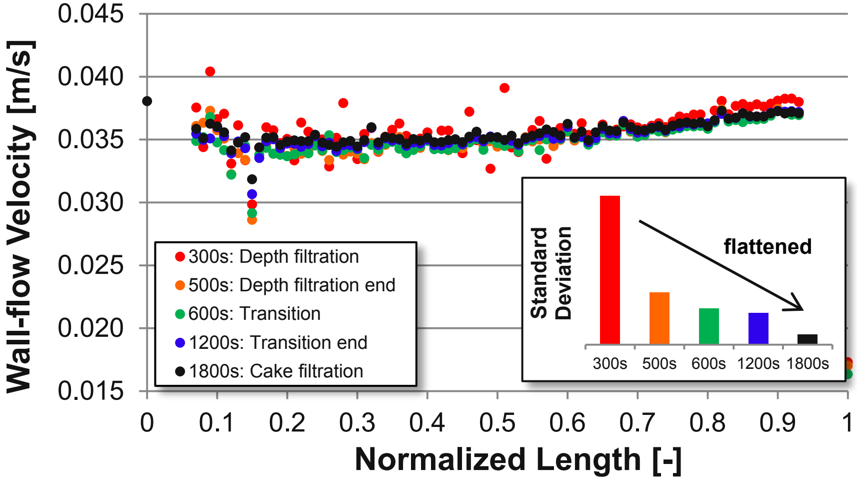
Pressure drop - overall



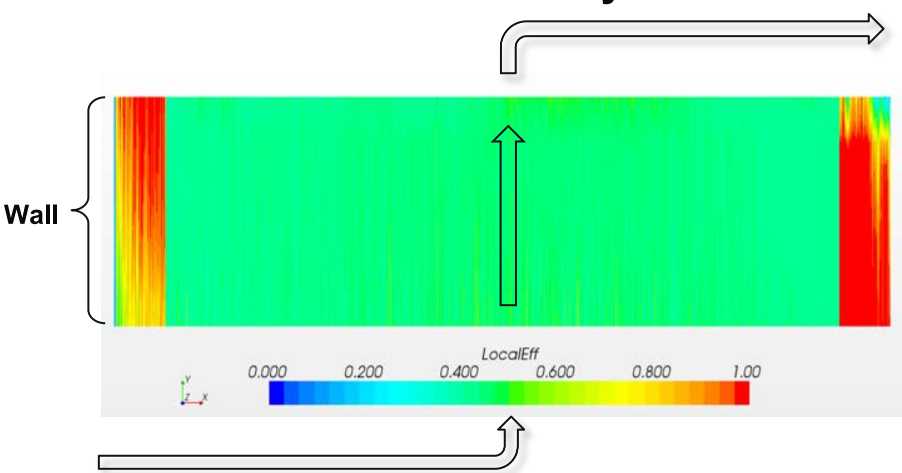
Soot cake profile



Wall-flow velocity profile



Local collection efficiency



Future Work

- Evaluate the filtration/regeneration performance for various filter models.
- Evaluate filtration/regeneration performance with catalyzed GPF.
- Evaluate kinetics of soot oxidation from the GDI engine with different compositions of reactant gases, using TGA and DSC
- Characterize the physical properties of PM emissions from the GDI engine as a function of engine operating condition, sampling position, and fuel injection timing.
- Characterize soot cake deformation during oxidation at various ambient conditions, using E-SEM.
- Conduct numerical modeling for G(D)PF regeneration at various conditions

Summary

- Strategies for low pressure drop and high regeneration efficiency were proposed by controlling the flow condition (*Pe*) and filter porosity, respectively.
- GDI engine performance (torque, BSFC) was evaluated for virtual GPF installation before the catalyst.
- Lean-burn conditions slightly increased O_2 concentration after the catalyst, while NOx conversion efficiency decreased quite a bit.
  - Lean-burn operation may not be applicable to regeneration after 3WC.
  - Fuel-cut effects will be evaluated.
- E-SEM experiments showed a potential to examine the in-situ oxidation behaviors of soot cake at a high spatial resolution.
- TEM analyses revealed that GDI engine generated numerous nanoparticles and two different size categories of aggregates. In addition, nanostructure analysis for E20-derived soot particles found different levels of graphitization (280° bTDC).
- Numerical modeling was successfully conducted for soot-laden flow in a cordierite filter, in which the self-developed user subroutines were implemented to the CFD code.

Accomplishment

- Publications
  - Journals (2)
    - *Chong, H., Aggarwal, S., Lee, K., Yang, S., and Seong, H.: "Experimental Investigation on the Oxidation Characteristics of Diesel Particulates Relevant to DPF Regeneration," Journal of Combustion Science and Technology (2012).*
    - *Lee, K., Seong, H., and Choi S.: "Detailed Analysis of Kinetic Reactions in Soot Oxidation by Simulated Diesel Exhaust Emissions," 34th International Symposium on Combustion (2012).*
  - Conference Proceedings and Workshops (4)
    - *Seong, H, Lee, K., and Choi, S.: "Characterization of Particulate Morphology, Nanostructures, and Sizes in Low-Temperature Combustion with Biofuels," SAE 2012-01-0441.*
    - *Seong, H. and Lee, K.: "Kinetic Study on Soot Oxidation by Simulated Diesel Gas Emissions," 2012 CLEERS Workshop, Dearborn, MI, May 2, 2012.*
    - *Choi, S., Lee, K, and Seong H..: "Characterization of Pore Structures in Diesel Particulate Filters by Mercury Intrusion Porosimetery, optical Imaging, and X-Ray Micro-tomography," AFS 2012 Annual Conference, Boca Raton, FL, June 6, 2012.*
    - *Lee, K., Seong, H., Church, W., and McConnell, S.: "Examination of Particulate Emissions from Alcohol Blended Fuel Combustion in a Gasoline Direct Injection Engine," 2012 COMODIA, Fukuoka, Japan, July 23-26, 2012.*

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