Advances in Multi-Functional Filter-Reactor Systems

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Project: Innovative Particle Trap SYstem for Future Diesel Combustion Concepts (IPSY)

Consortium:

- FEV Motorentechnik (Aachen, DE)
- Aerosol & Particle Technology Lab. CERTH (Thessaloniki, GR)
- IFP Energies Nouvelles (Solaize, FR)
- Universidad Politecnica de Valencia (Valencia, ES)
- Fundaçion Cidaut (Madrid, ES)
- Instituto Motori (Napoli, IT)
- Institute for Combustion Engines, RWTH Aachen University (Aachen, DE)
- Cracow University of Technology (Cracow, PL)

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1.8 MEuros

Outline

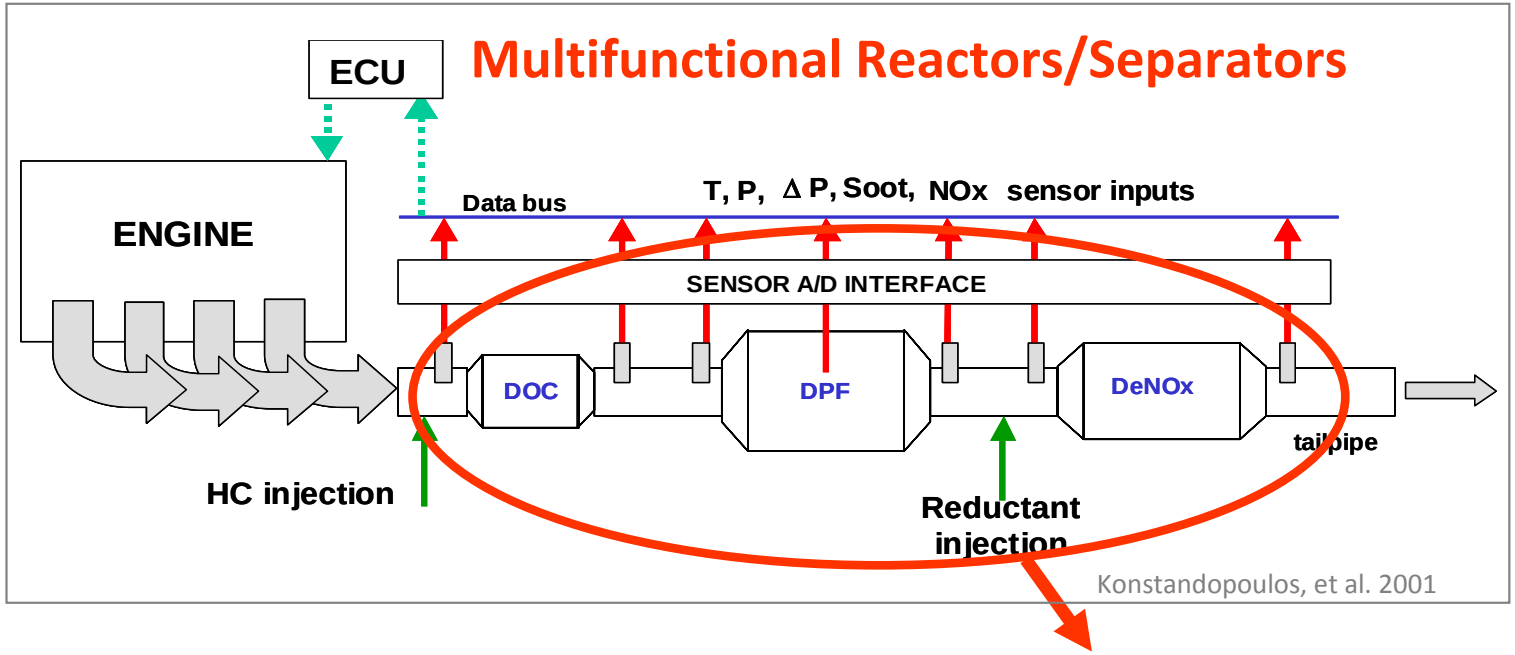
- Motivation
- Multi-Functional Filter-Reactor (MFR) system
- Performance under conventional combustion conditions
- The aged MFR
- Performance under alternative combustion conditions
- Analysis of soot from conventional and alternative combustion
- Fuel consumption prediction

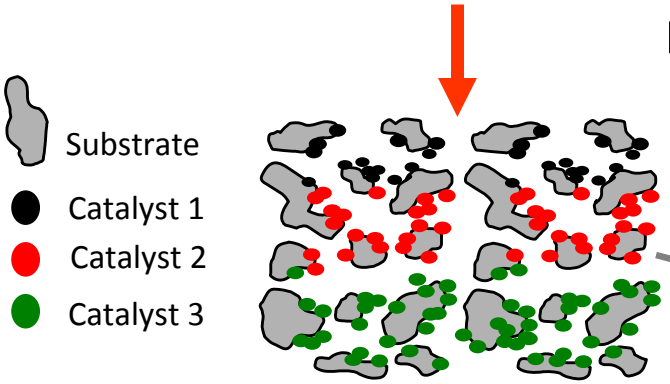
- Conclusions

Motivation

Emission Control Components

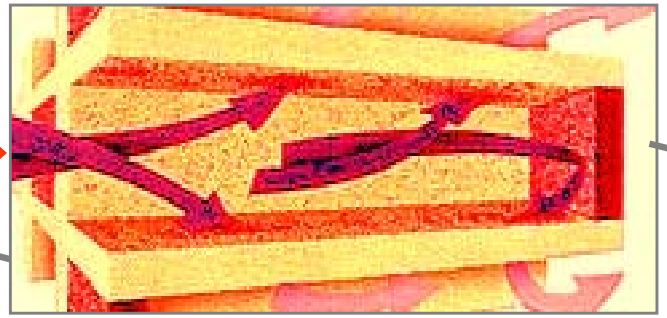
DOC:Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter
DeNOx: NOx Trap or SCR Converter
(SCR: Selective Catalytic Reduction)
ECU: Engine Control Unit





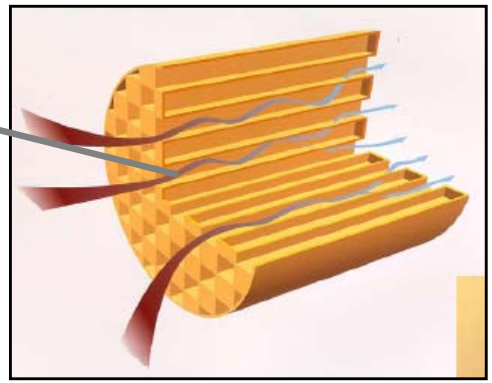
Multifunctional Porous Wall

Exhaust Flow



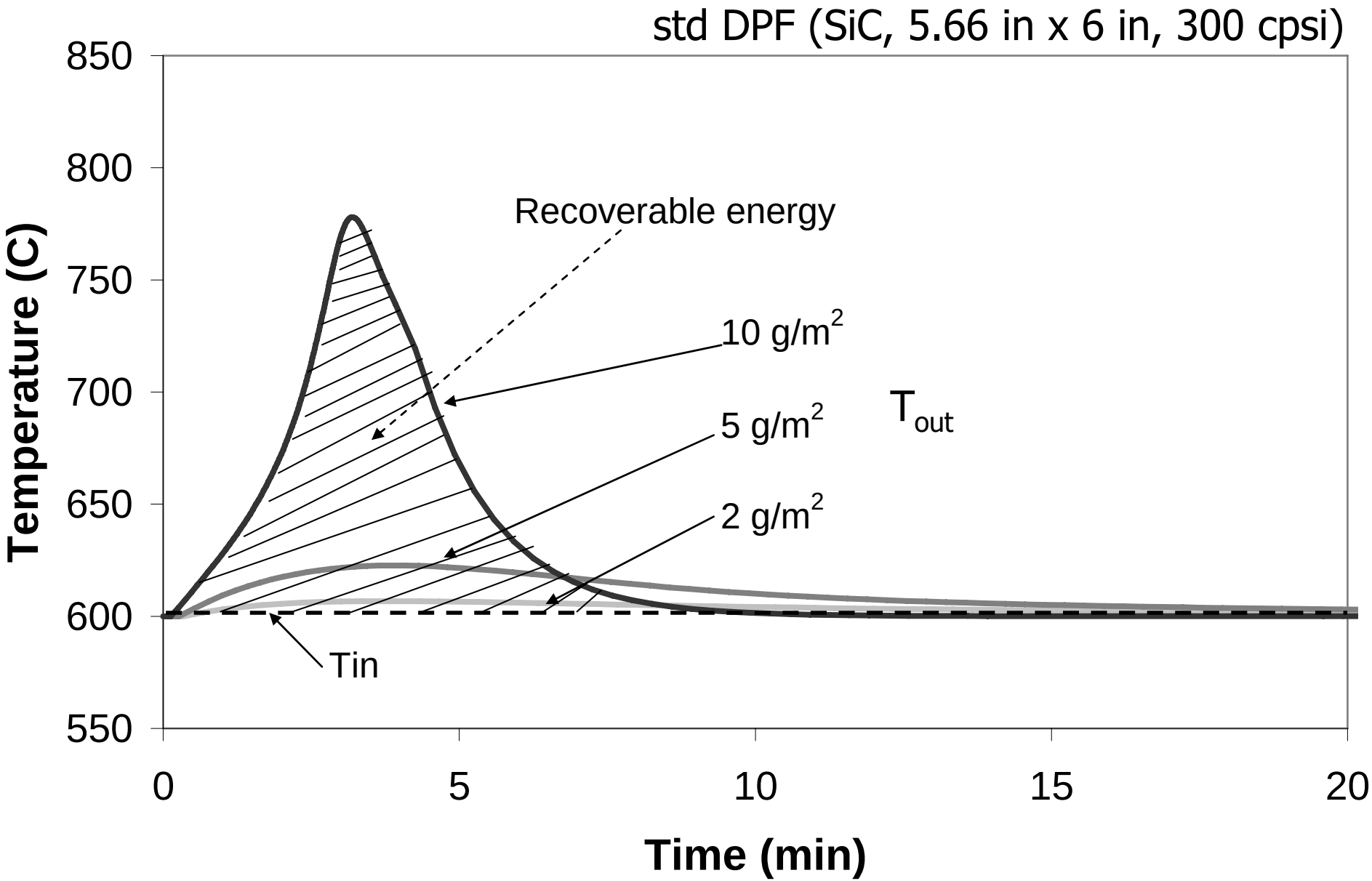
Single Channel

Integration into "Single Brick"



DPF as a Multifunctional Reactor/Separator

Recoverable Energy from Regeneration



Multi-Functional Filter-Reactor (MFR)

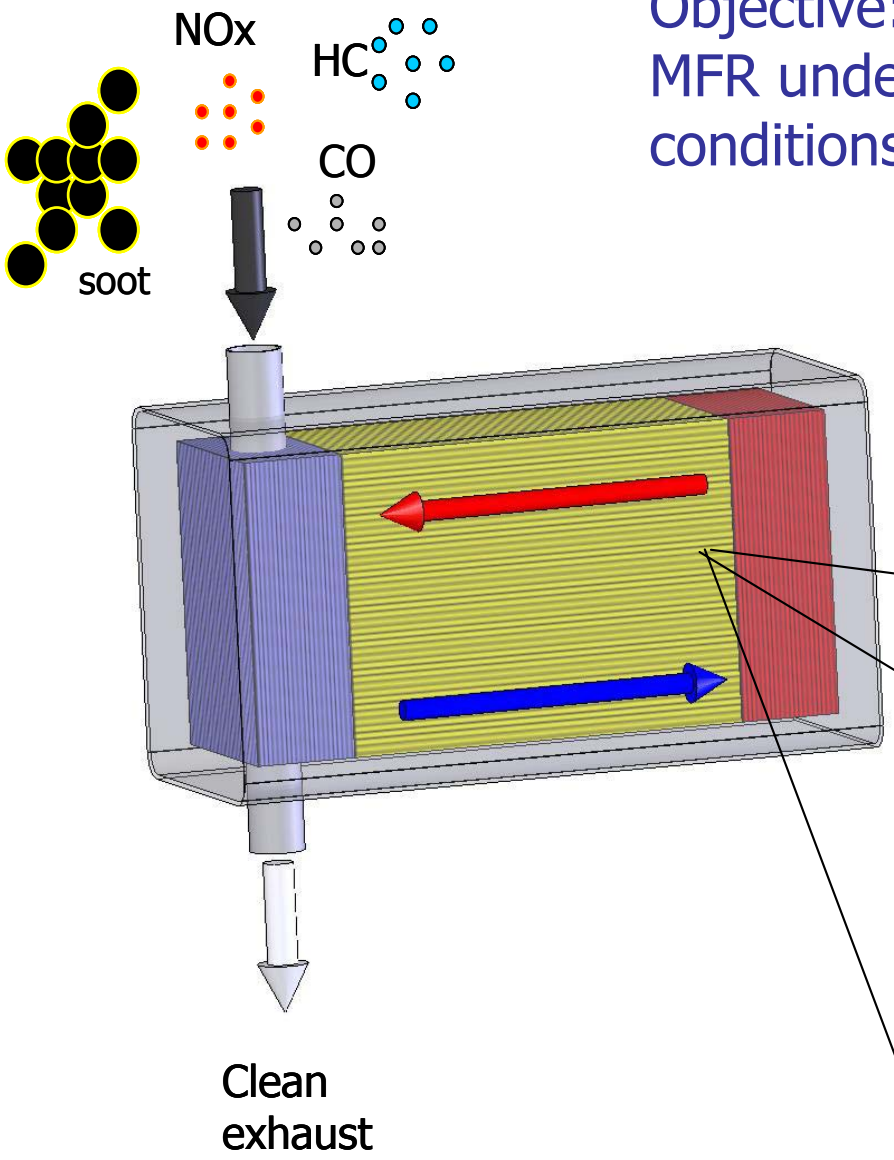
(The initial development of the MFR has been described in SAE 2009-01-0287)

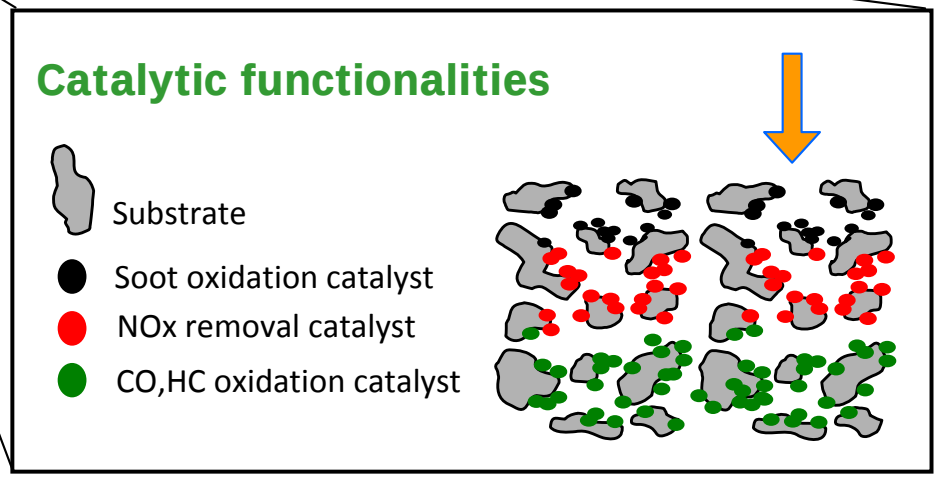
The MFR is a "single brick" solution which incorporates the following functionalities:

- Heat management with internal heat recovery
- Direct and indirect soot oxidation
- Gas species (CO, hydrocarbons) oxidation
- Very high filtration efficiency from clean condition

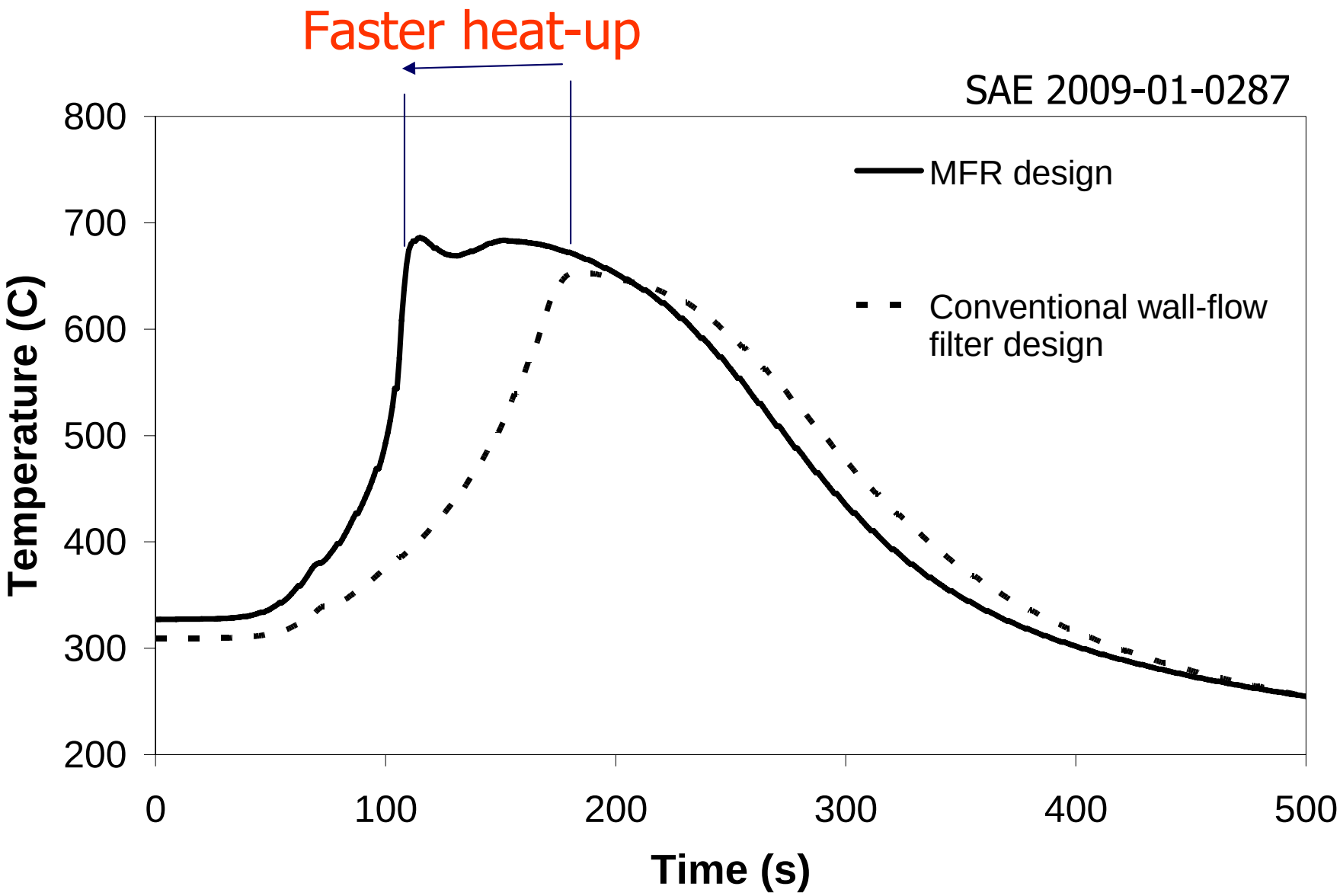
Multi-Functional Reactor (MFR)

Objective: Develop and assess the performance of the MFR under conventional and alternative combustion conditions.





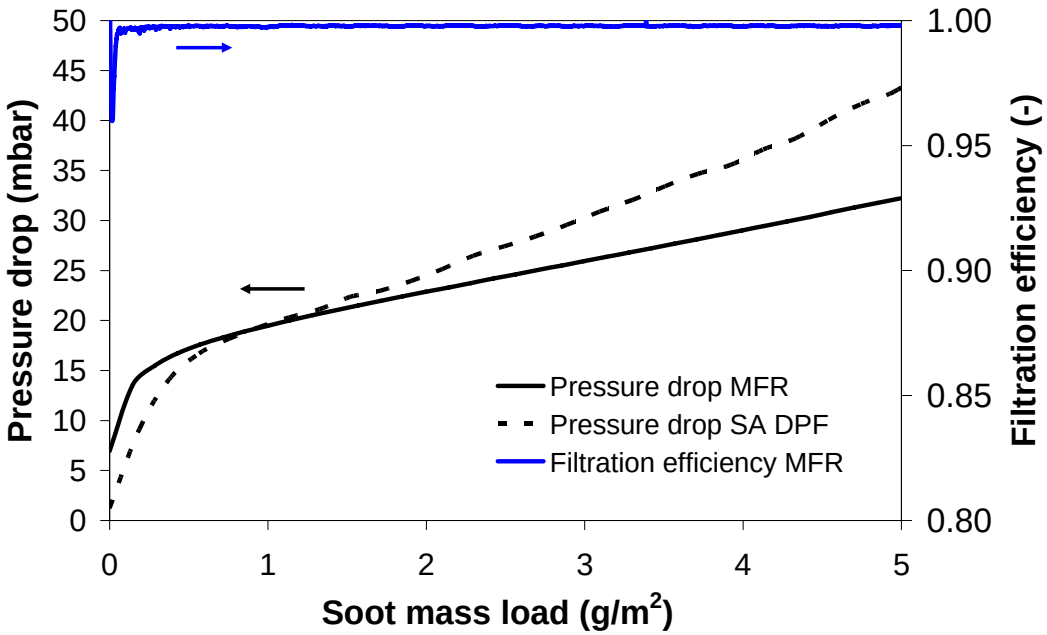
Thermal Behavior During Regeneration



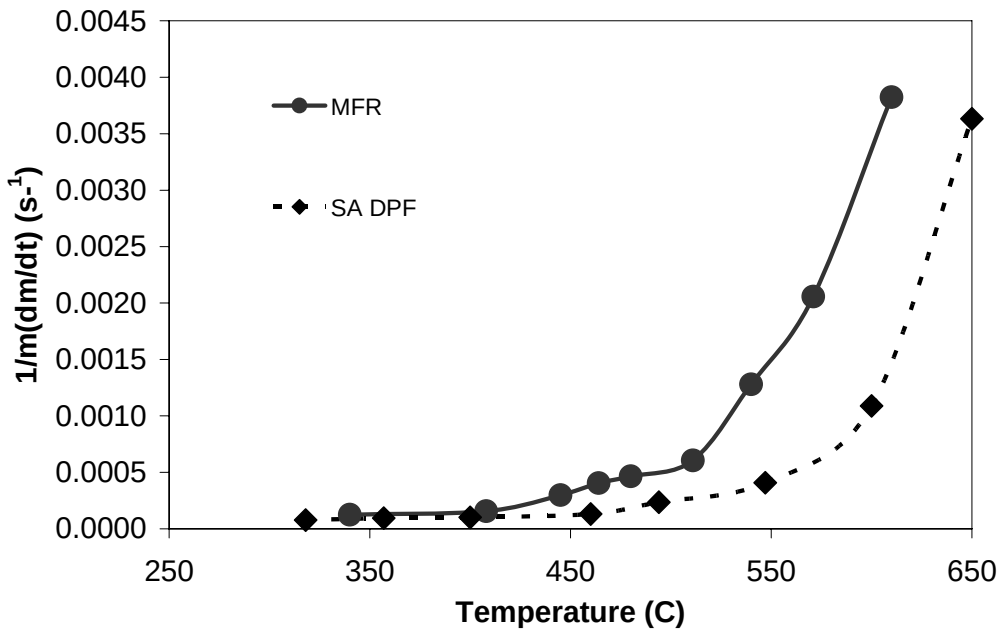
MFR Pressure Drop and Soot Oxidation

SAE 2009-01-0287

Pressure Drop



Soot Oxidation Rate



Favorable pressure drop behavior and higher soot oxidation activity from the (fresh) MFR.

SA: Supplied for Assessment/Benchmark Catalyzed DPF

The aged MFR

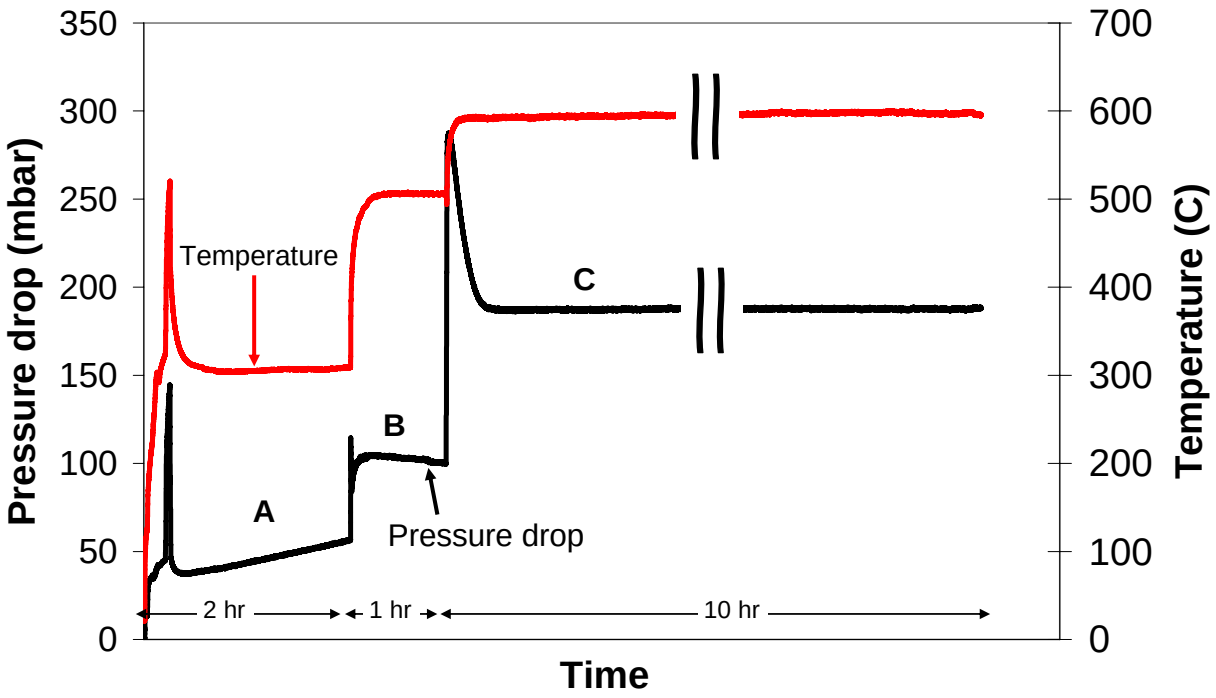
Aging procedure (equivalent to regenerations for 100,000 km of normal vehicle driving)

A: Loading (2000 rpm, BMEP: 5 bar, T_{exh}=310 °C) → 2 hr

B: Oxidation (1500 rpm, BMEP: 9 bar, T_{exh}=500 °C) → 1 hr

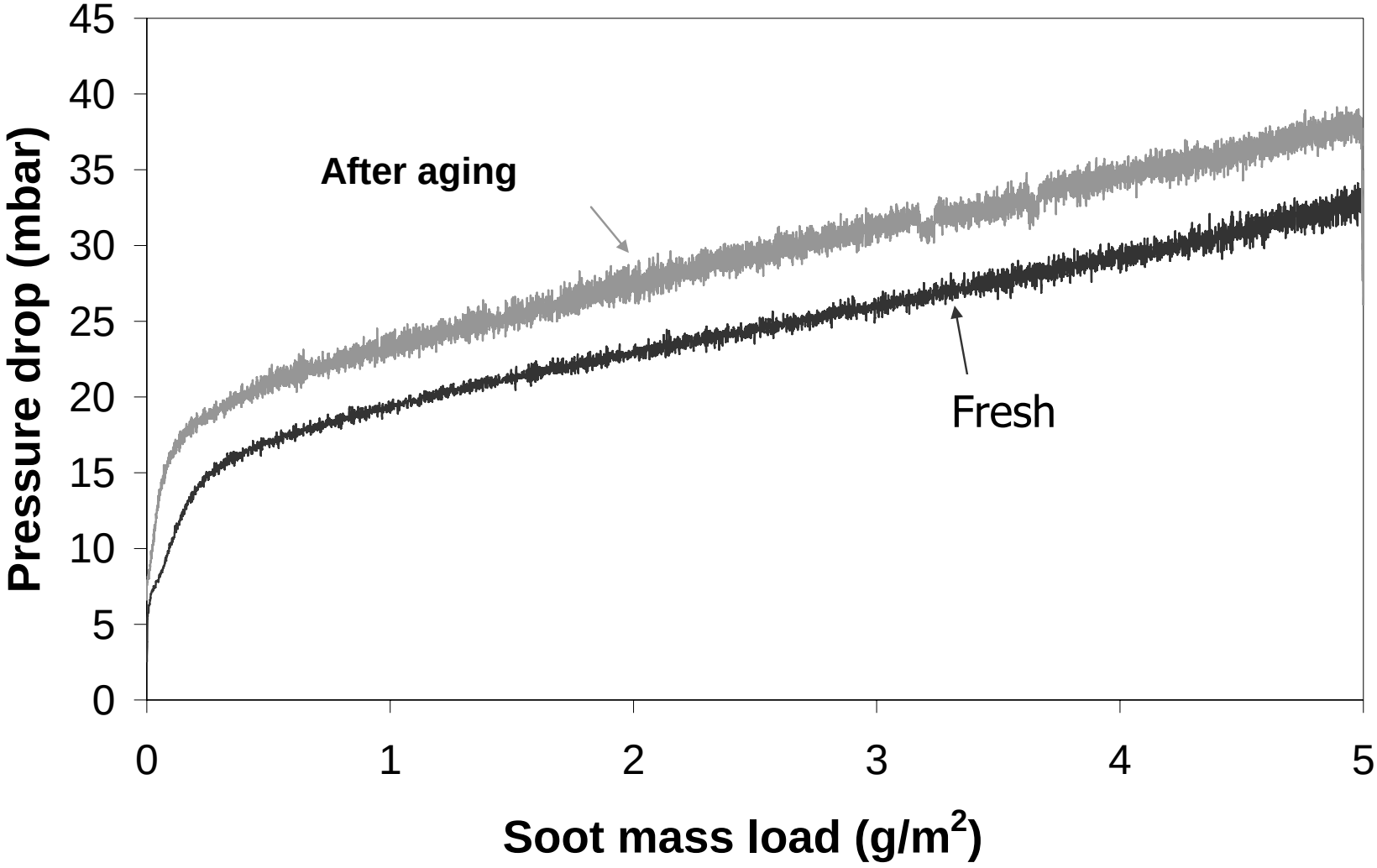
C: Continuous Regeneration (3000 rpm, BMEP: 10 bar, 600 °C) → 10 hr

Procedure repeated 5 times



Pressure drop for fresh and aged MFR

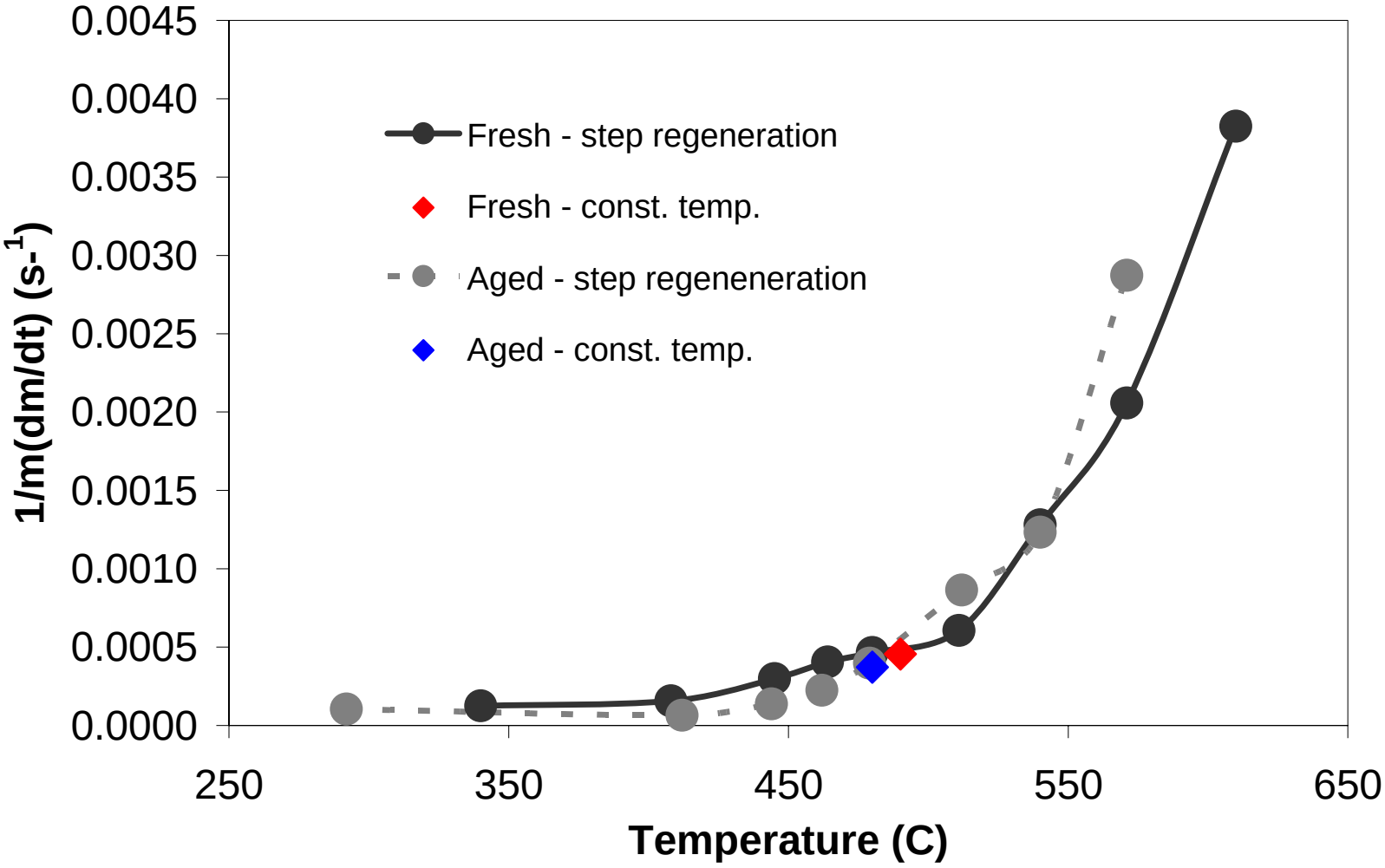
Steady state engine operation conditions 1500 RPM, 3 bar, 250 °C



Increase in clean and loaded pressure drop attributed mainly to some ash accumulation.

Soot oxidation for fresh and aged MFR

Constant temperature and step temperature regeneration protocols as described in past SAE Papers 2005-01-0670, 2004-01-0694



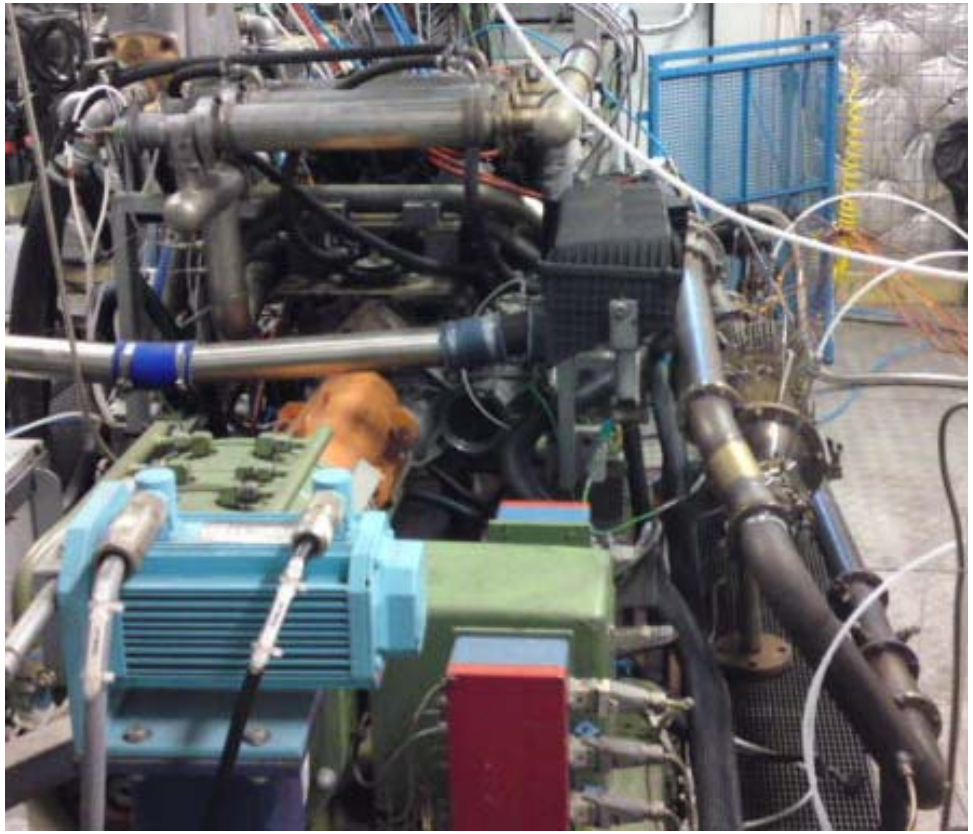
Aging did not affect the soot oxidation performance.

MFR performance – alternative combustion

HCCI conditions :

Narow Angle Direct Injection (NADI™) concept employed on a conventional 4 cylinder, 2.2 L, Euro 4, Diesel engine

- narrow injector cone angle
- Prototype EGR
- Reduced compression ratio



Analysis of soot particles

Analysis techniques:

- Elemental analysis (C, H)
- Transition Electron Microscopy (TEM)
- Thermo-Gravimetric Analysis (TGA)
  (under linear temperature ramp)
- Ex-situ µRaman Spectroscopy at ambient temperature

Samples:

- Carbon Black (CB)
- Soot from conventional combustion
- Soot from HCCI combustion

Elemental analysis

Sample	H/C (% w/w)
CB	0.0040
Conventional	0.0060
HCCI	0.0166

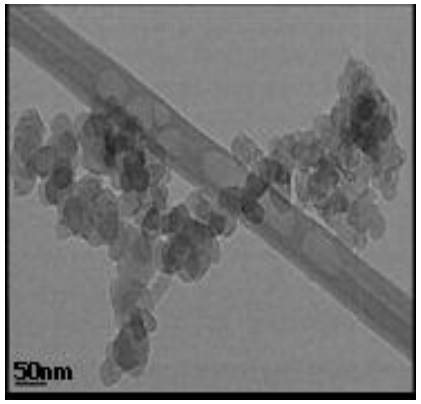
Higher hydrogen content in HCCI soot.

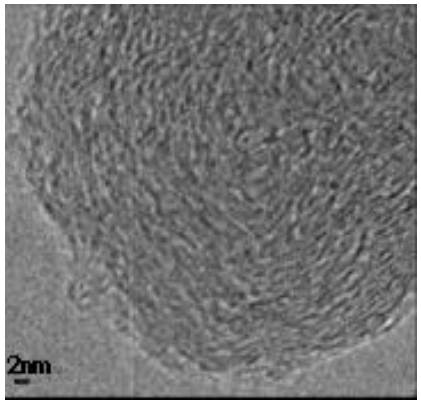
TEM Images

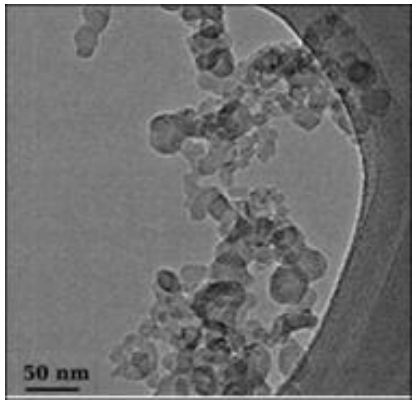
carbon black

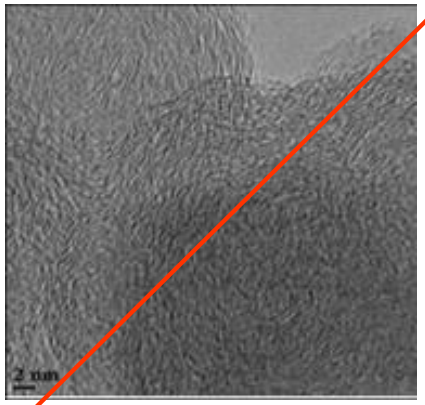
conventional

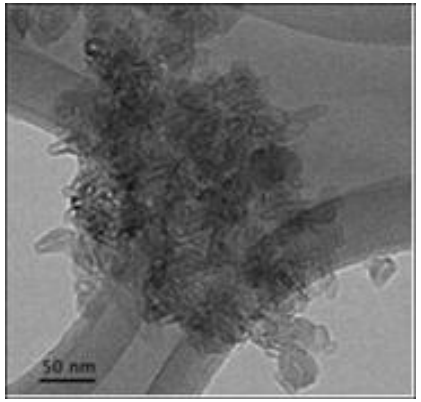
HCCI

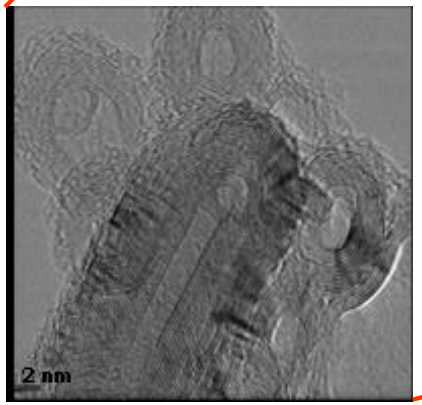




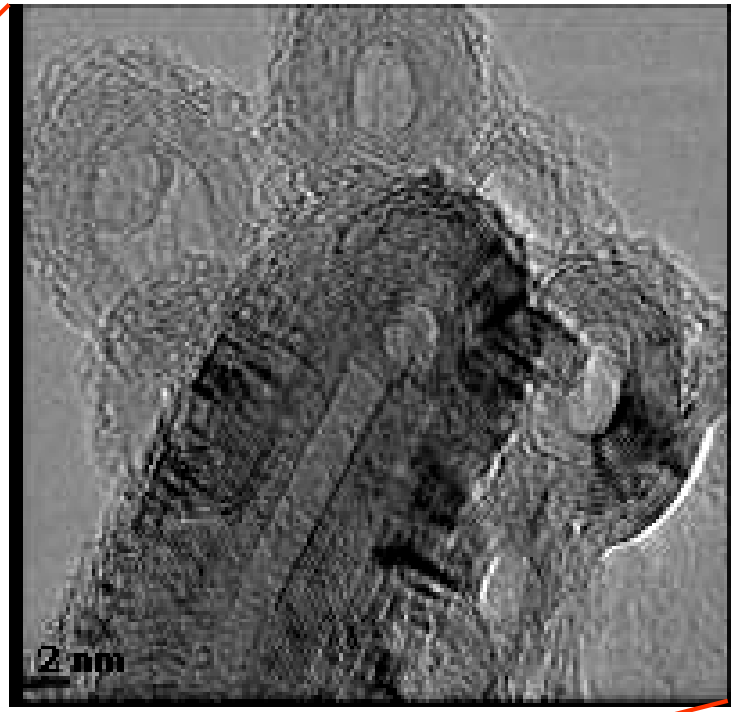








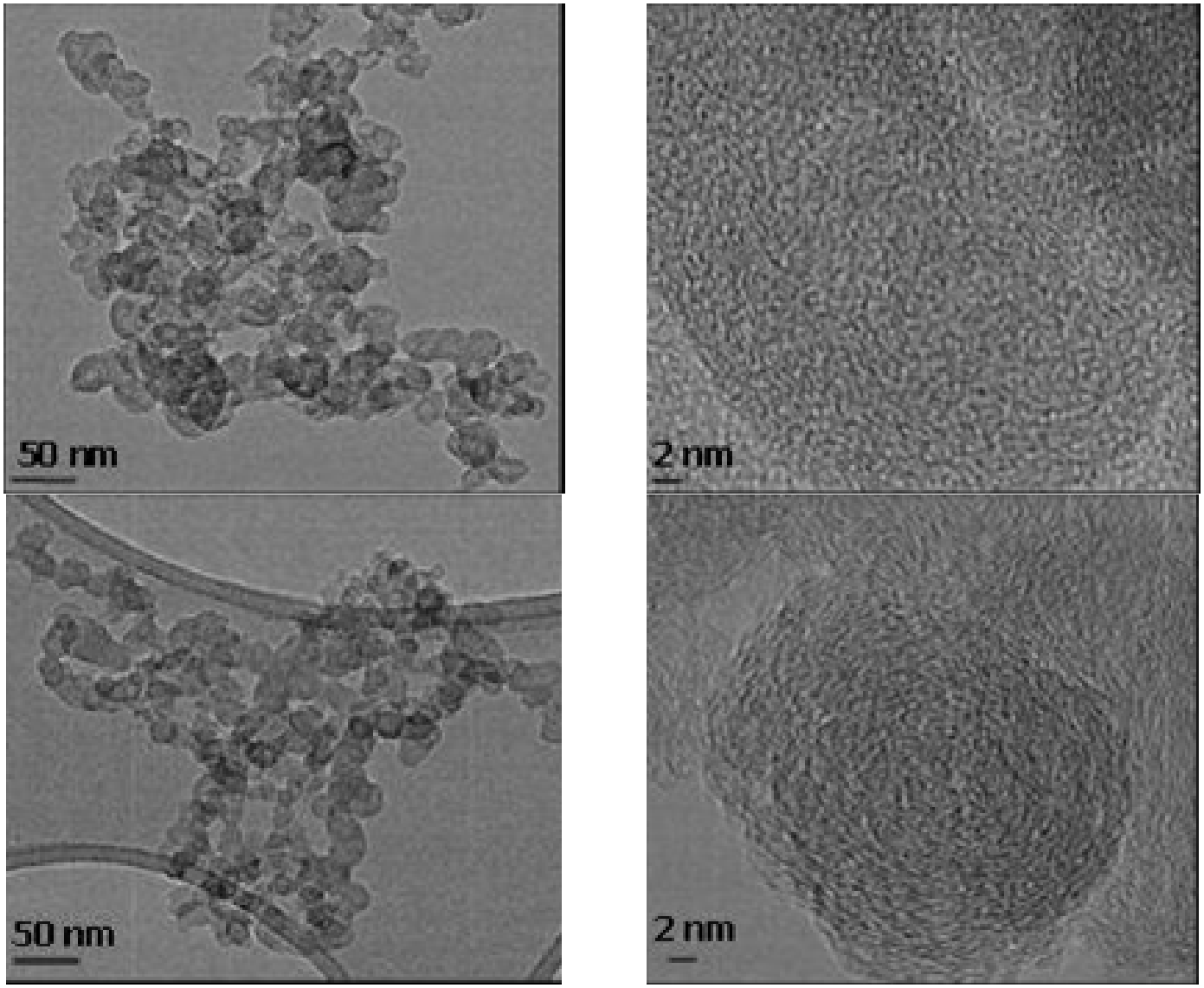
Minor differences in aggregate geometry but a core-shell structure observed at primary particle level for HCCI soot.



TEM analysis of partially oxidized samples (60 % burn off)

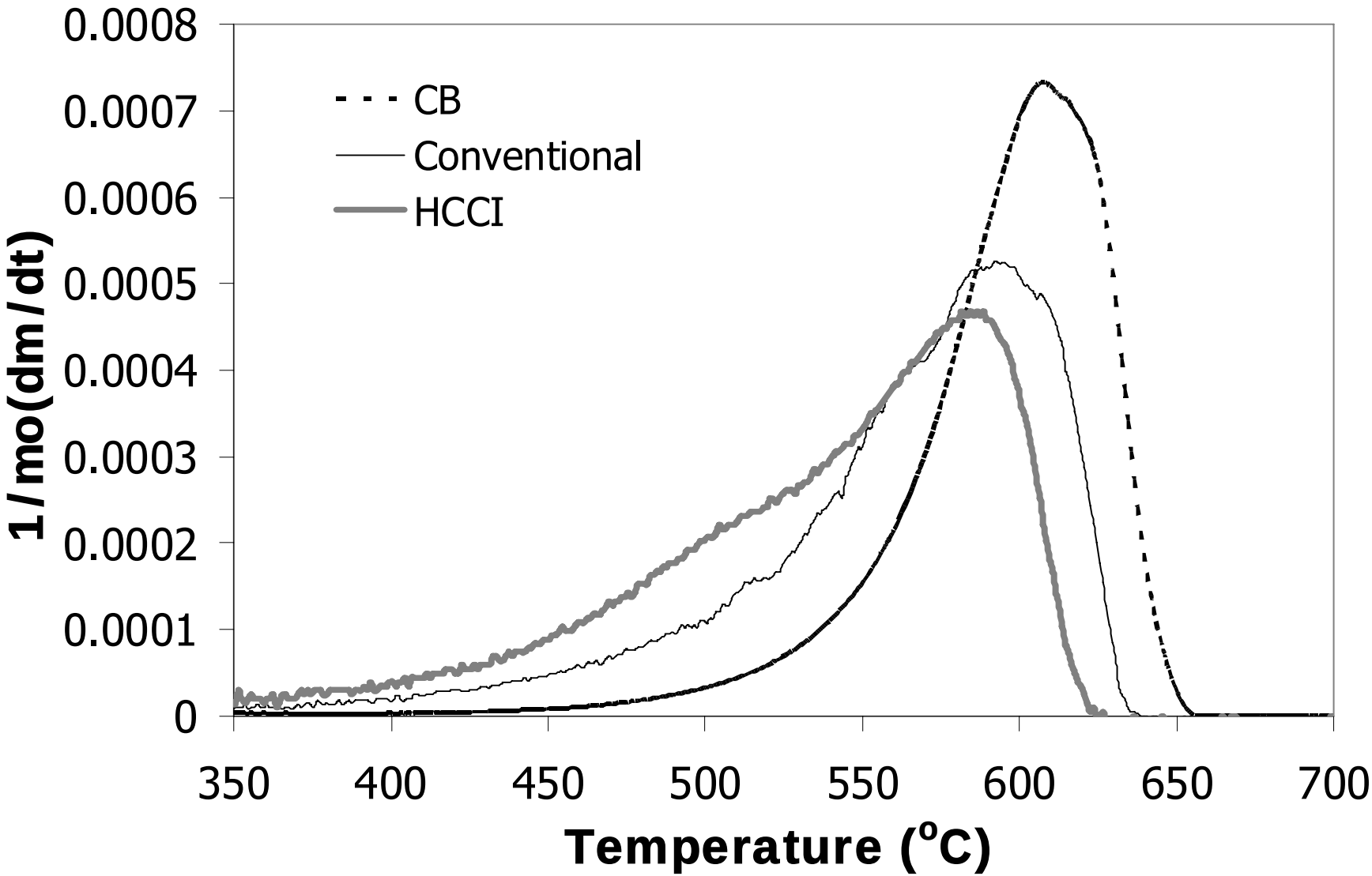
conventional

HCCI



Core-shell structure seems to disappear after partial oxidation.

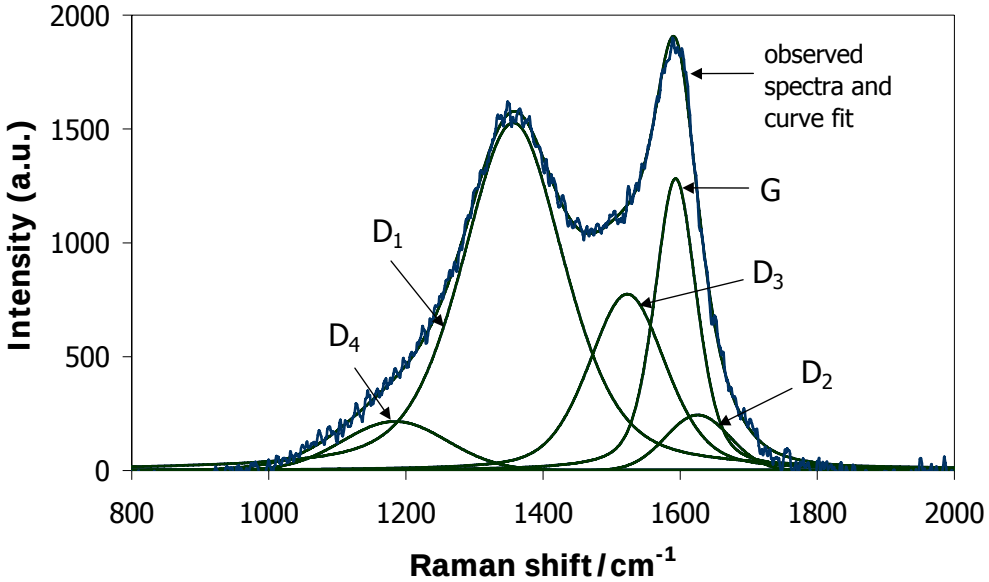
Thermogravimetric analysis of soot samples



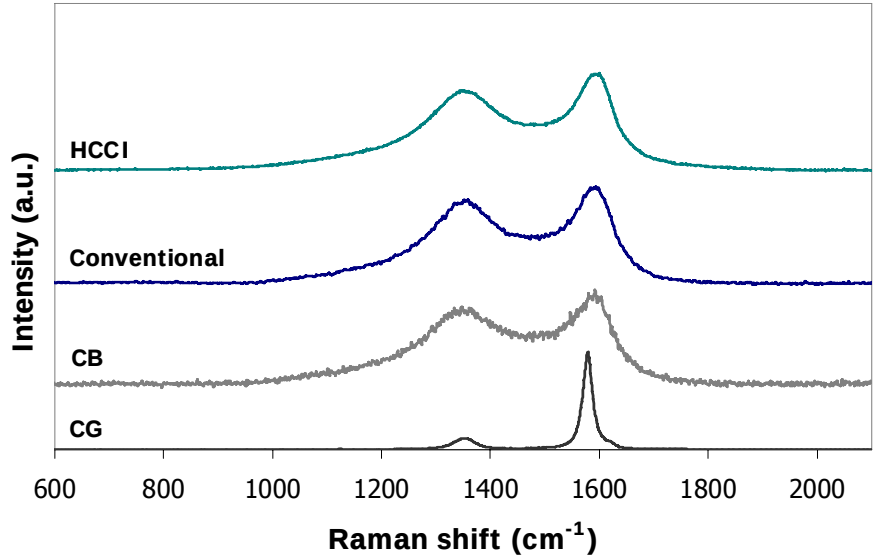
Linear temperature ramp 3 °C/min. HCCI soot relatively more reactive under TGA conditions.

Raman Spectroscopy

Curve for the first-order Raman Spectrum



Raman spectra of the soot samples

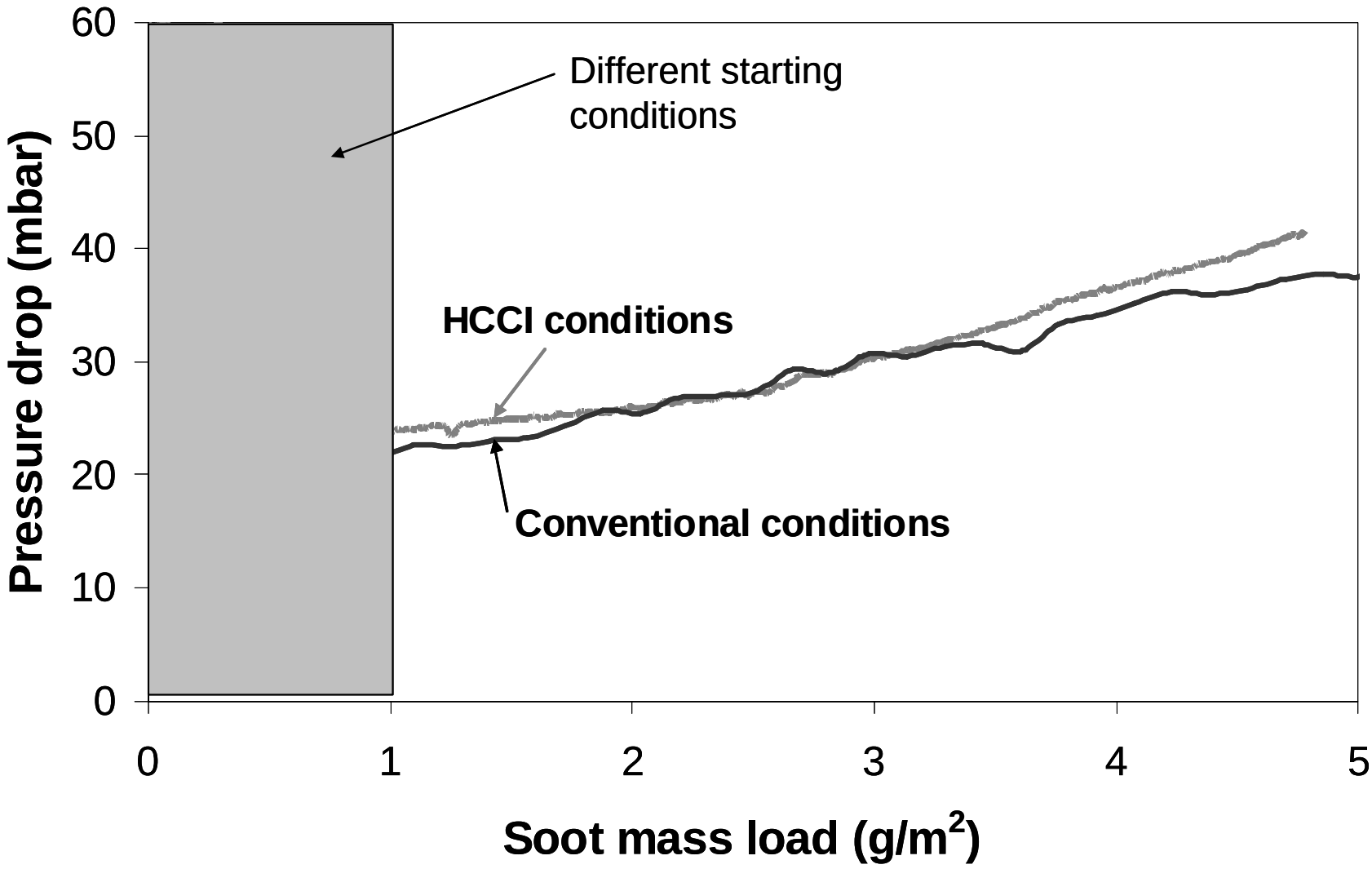


Sample	I_{D1}/I_G
HCCI	4.6 ± 0.20
Conventional	4.4 ± 0.10
CB	4.5 ± 0.15
CG	0.2 ± 0.15

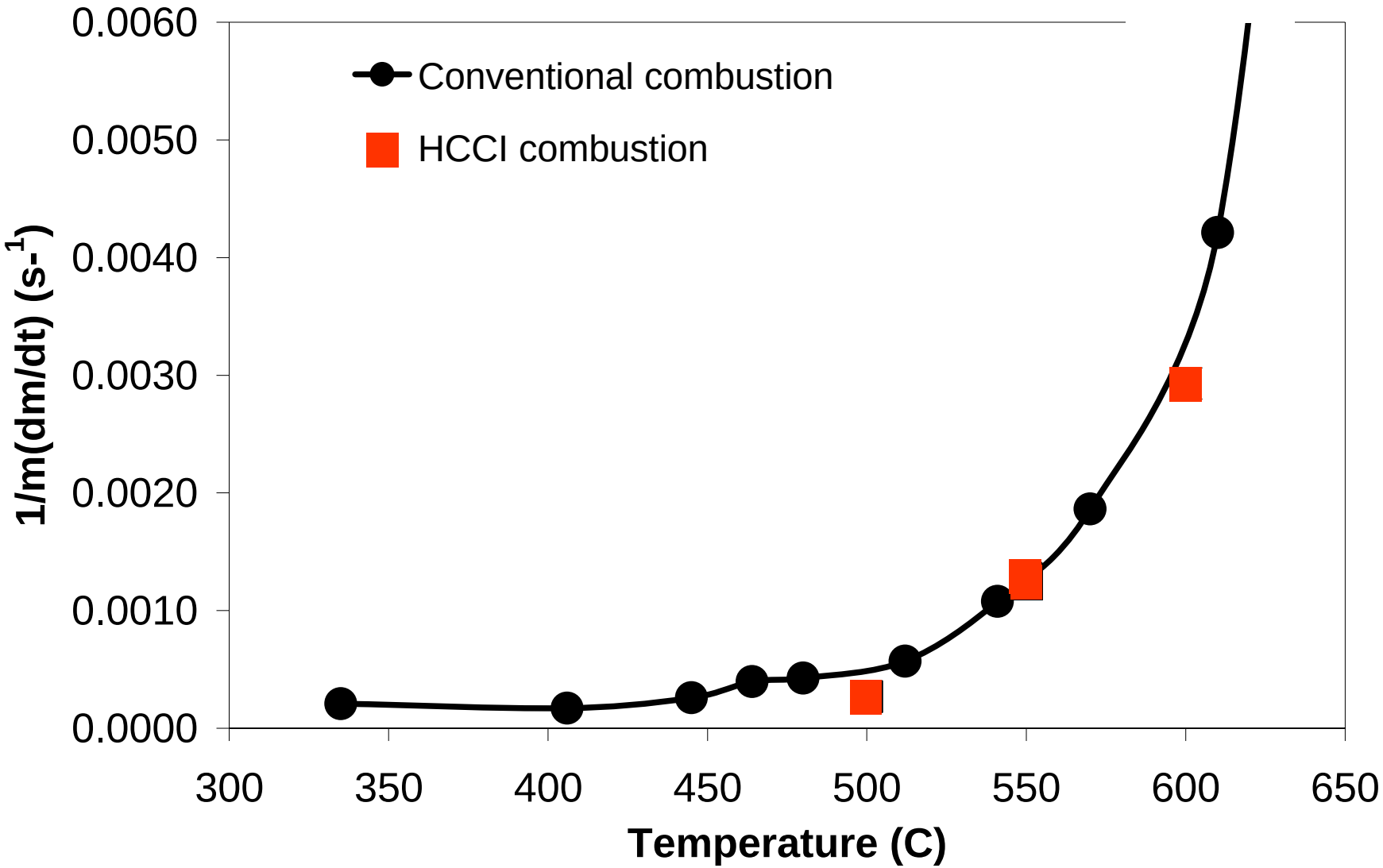
HCCI soot has similar degree of structural organization of its surface.

Pressure Drop

Same inlet filter temperature (230 °C) and exhaust mass flow rate (65 kg/hr) for HCCI and Conventional conditions

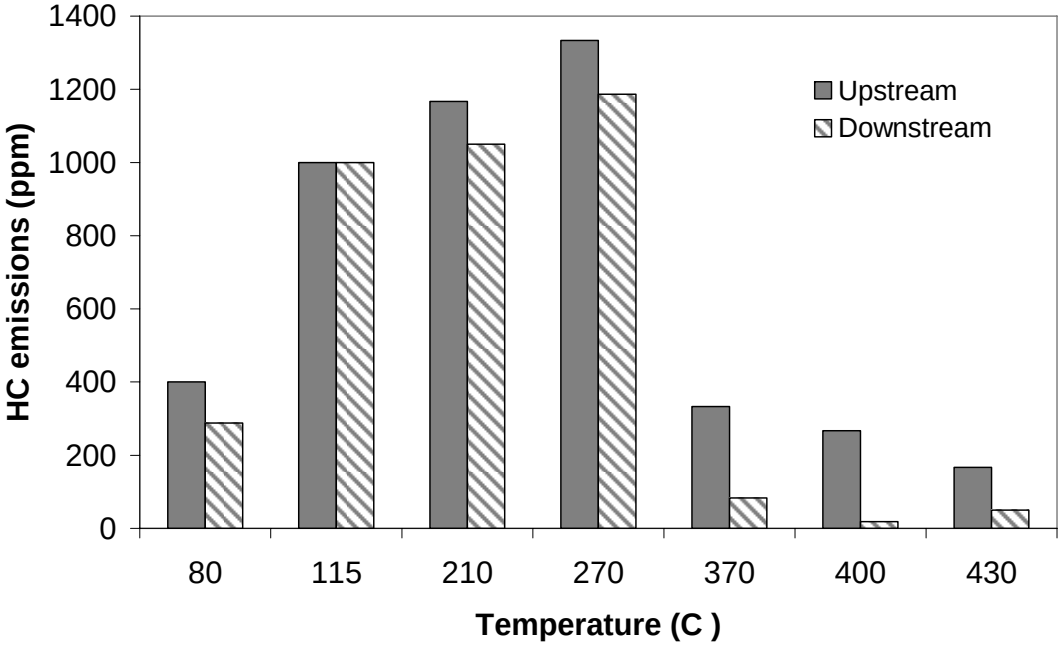


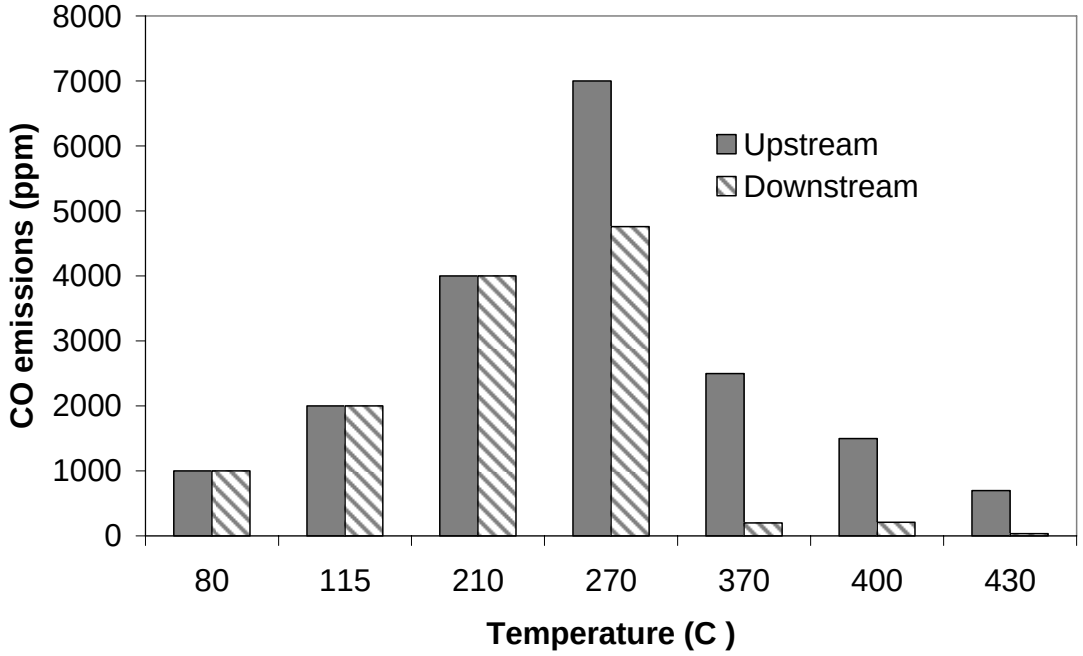
Soot oxidation



No difference seen for HCCI-loaded MFR in soot oxidation rates during const. temperature regeneration.

MFR effect on HC and CO emissions from HCCI mode





Need to improve the low temperature / HCCI gas oxidation activity

Note the quite high HC and CO emission levels at some HCCI test conditions, where some inhibition are expected to be present.

Fuel penalty simulation

Simulations based on NEDC and off-cycle FEV's driving pattern data from the High Efficiency Combustion System (HECS) engine.

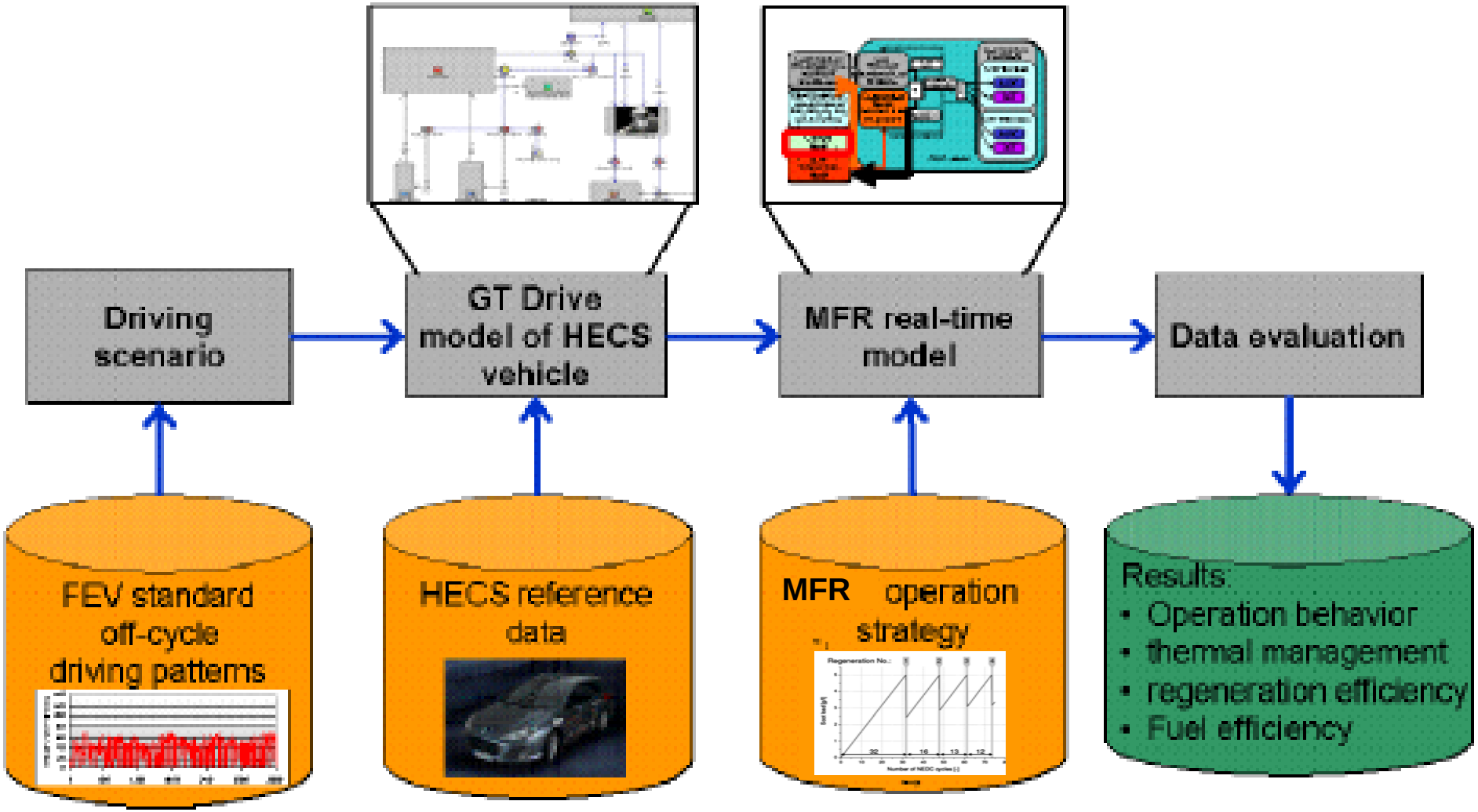
Engine characteristics:

- Downsized 1.6 litre 4-cyl. Diesel engine
- 80 kW/litre spec. power
- 2-stage boosting system
- High and Low Pressure EGR
- Advanced Cooling Concept
- 2000 bar Piezo injector
- Optimized Bowl with CR 15:1
- Variable Swirl Concept
- Advanced Control Strategies

Benefits:

- Fuel consumption reduction (~17 %)
- EU6 emissions w/o NOx aftertreatment
- High specific torque and power
- Robust combustion system

Layout of Simulation

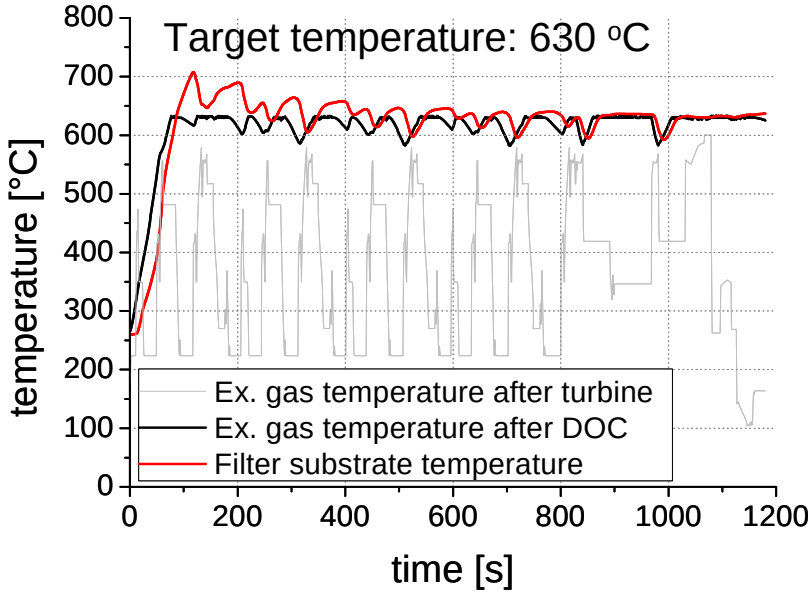


Investigation of target regeneration temperature under NEDC conditions

SA DPF

Target soot mass load:

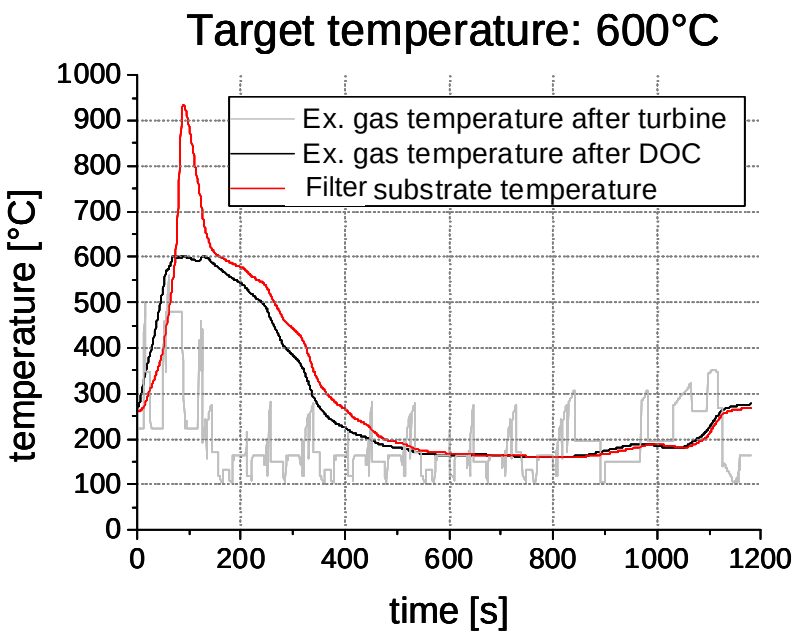
7 g/m^2

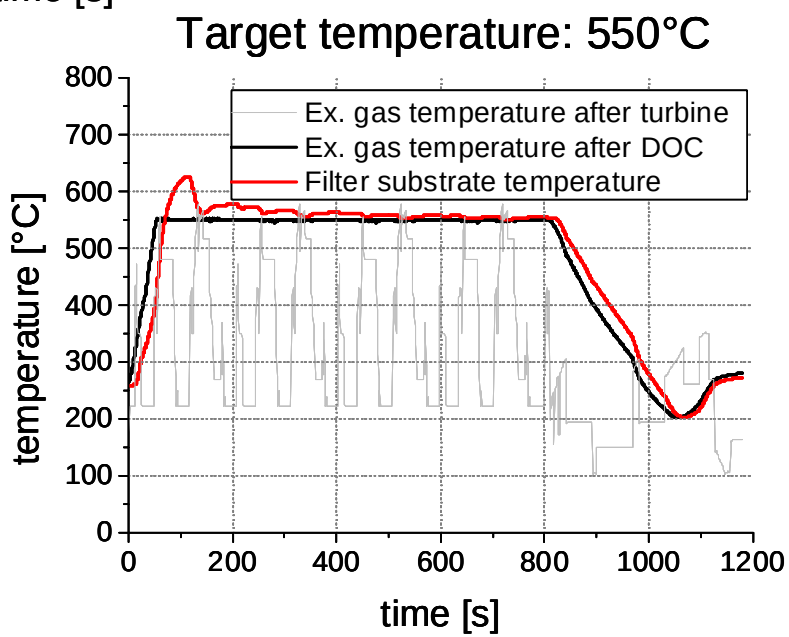


MFR

Target soot mass load:

5 g/m^2



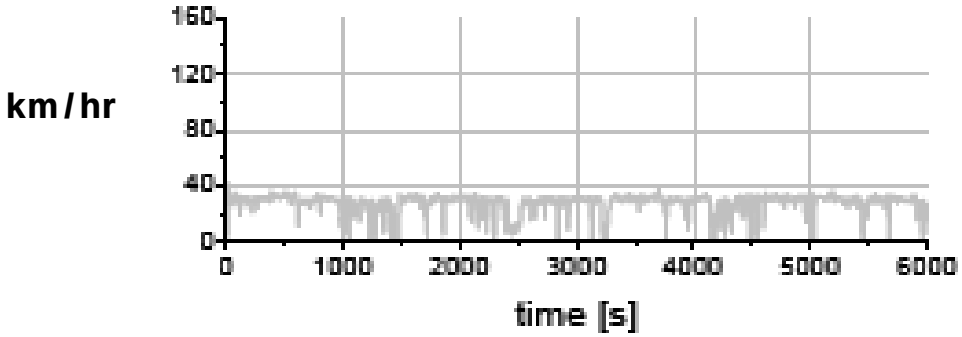


It was decided to use distinct regeneration strategies best suited to each system rather than a common one.

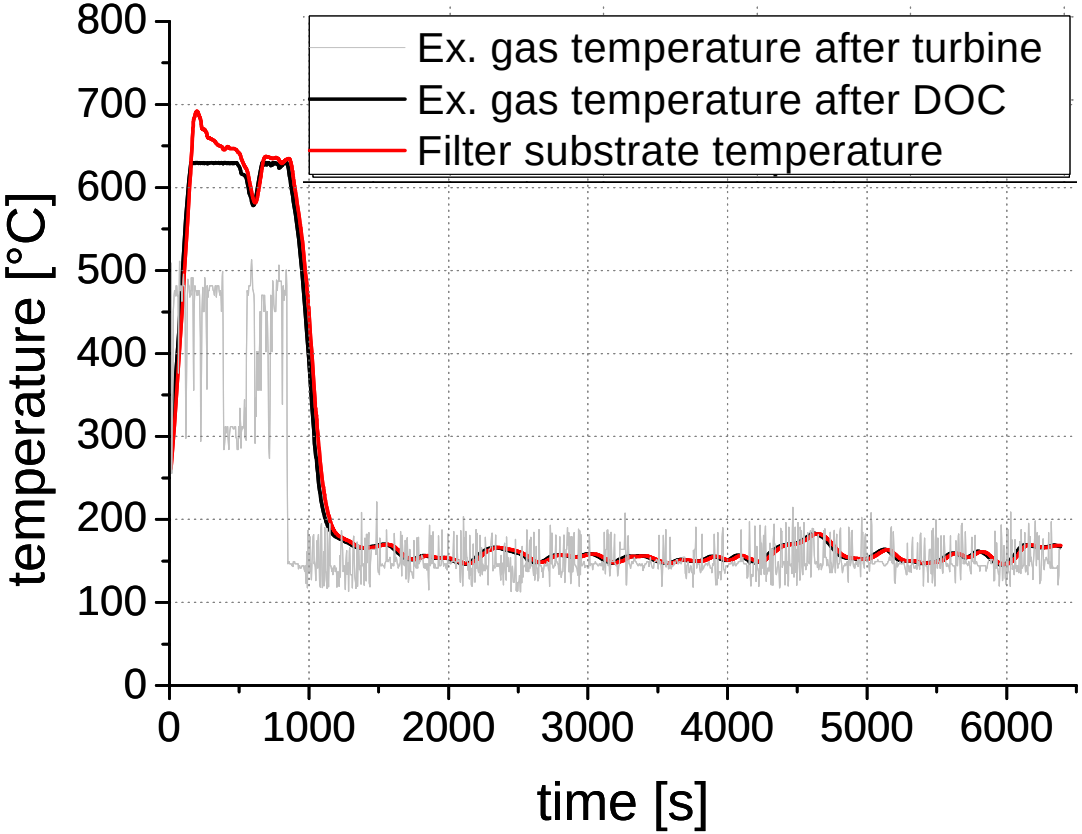
Regeneration strategy

	Target soot load to start regeneration	Target soot load to stop regeneration	Target exhaust gas temperature
SA DPF	7 g/m²	0.5 g/m²	630°C
MFR	5 g/m²	0.5 g/m²	550°C

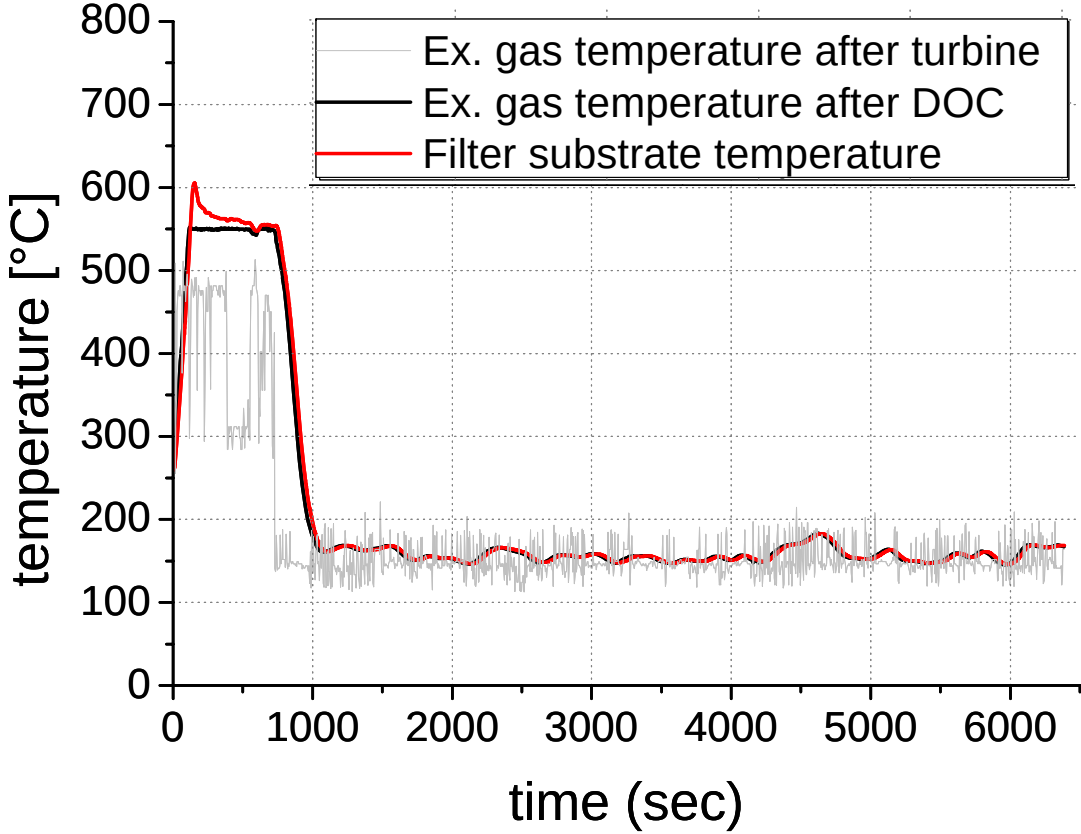
Temperatures during slow city cycle regeneration



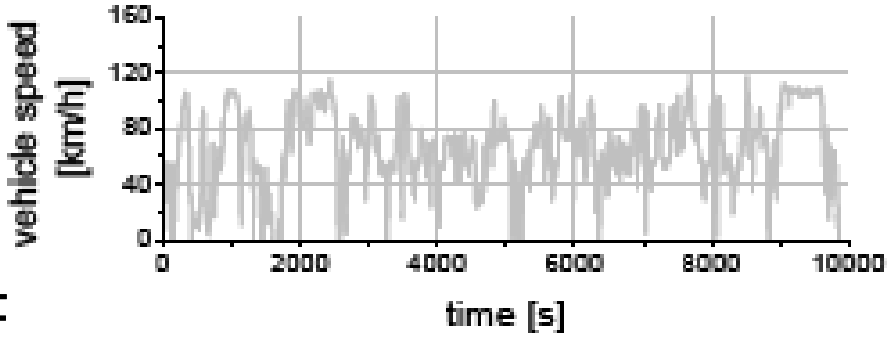
SA DPF



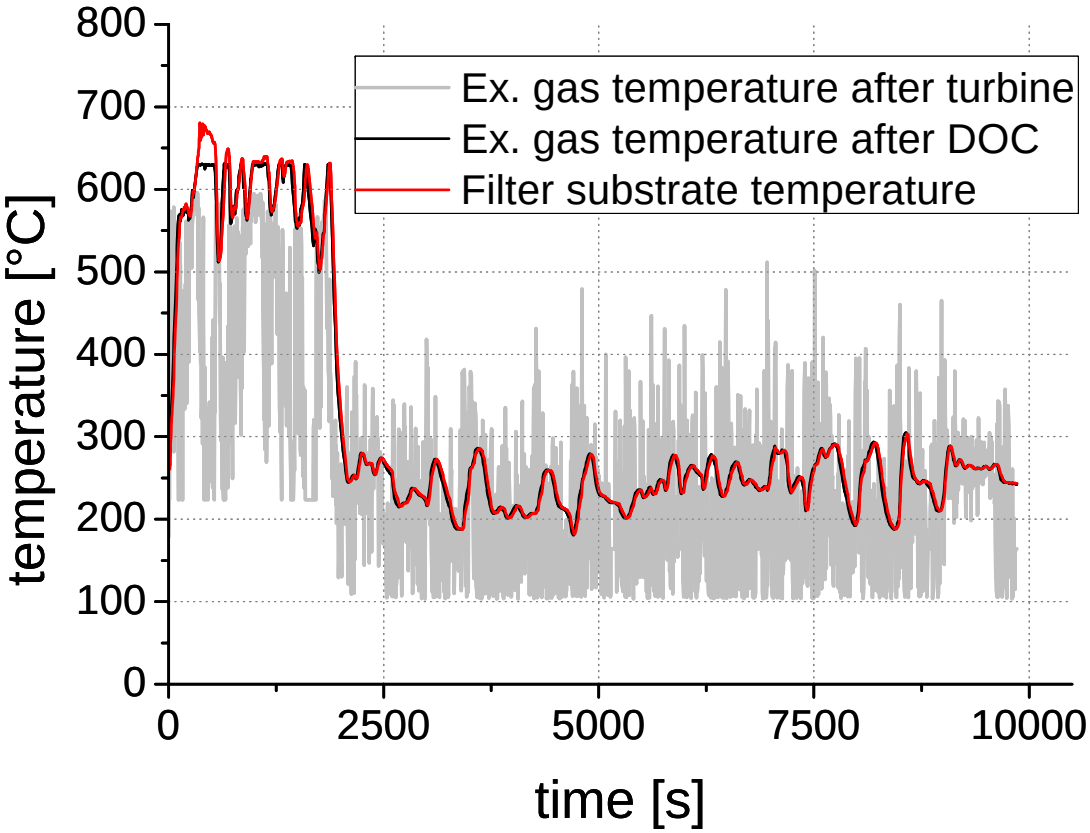
MFR



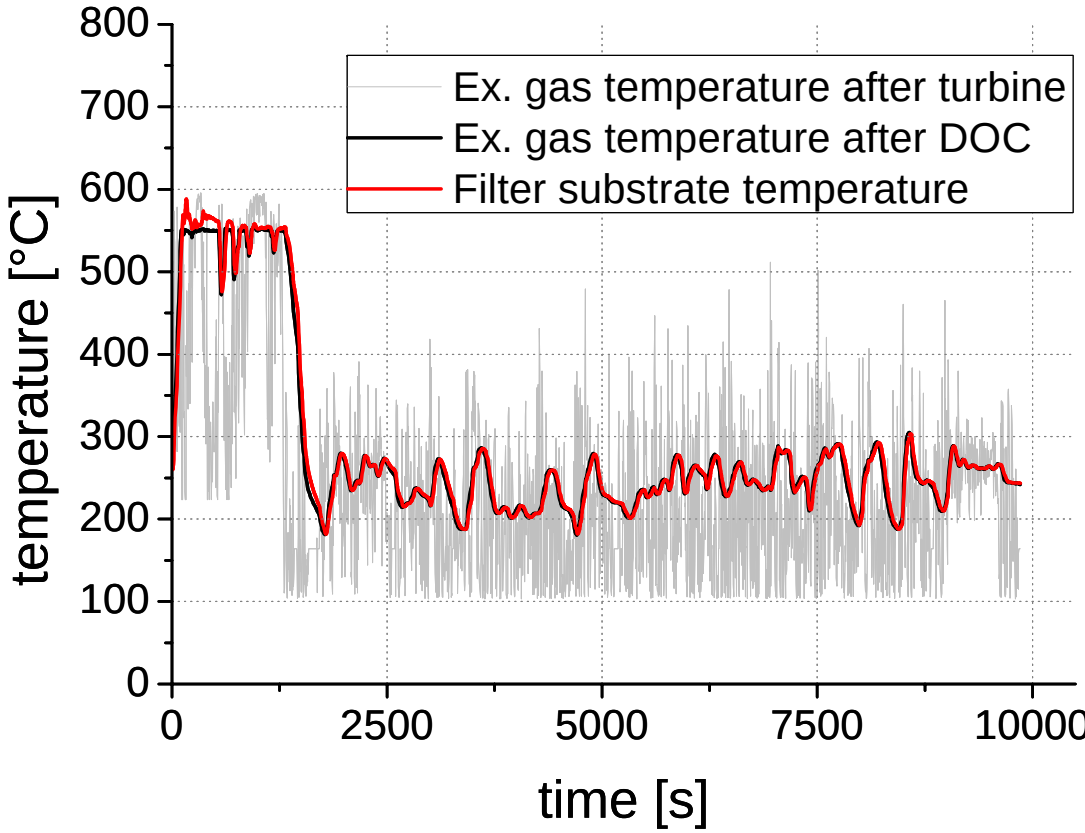
Temperatures during interurban cycle regeneration



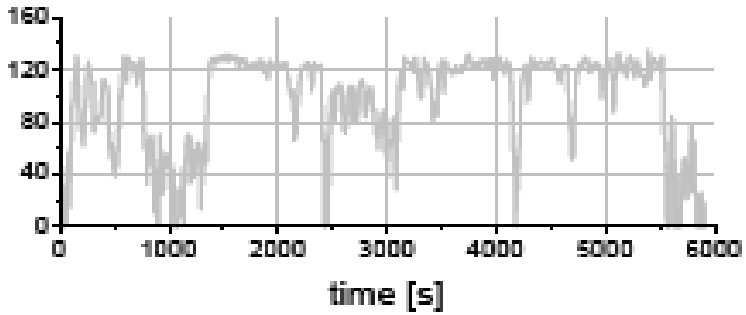
SA DPF



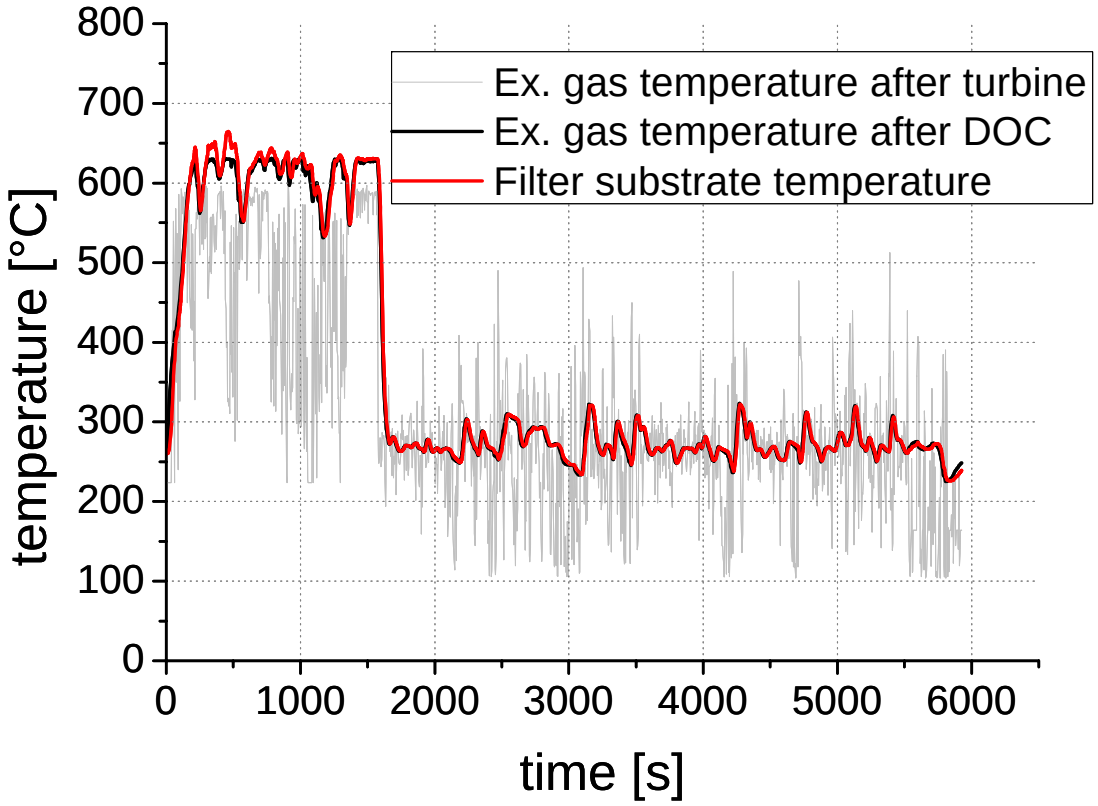
MFR



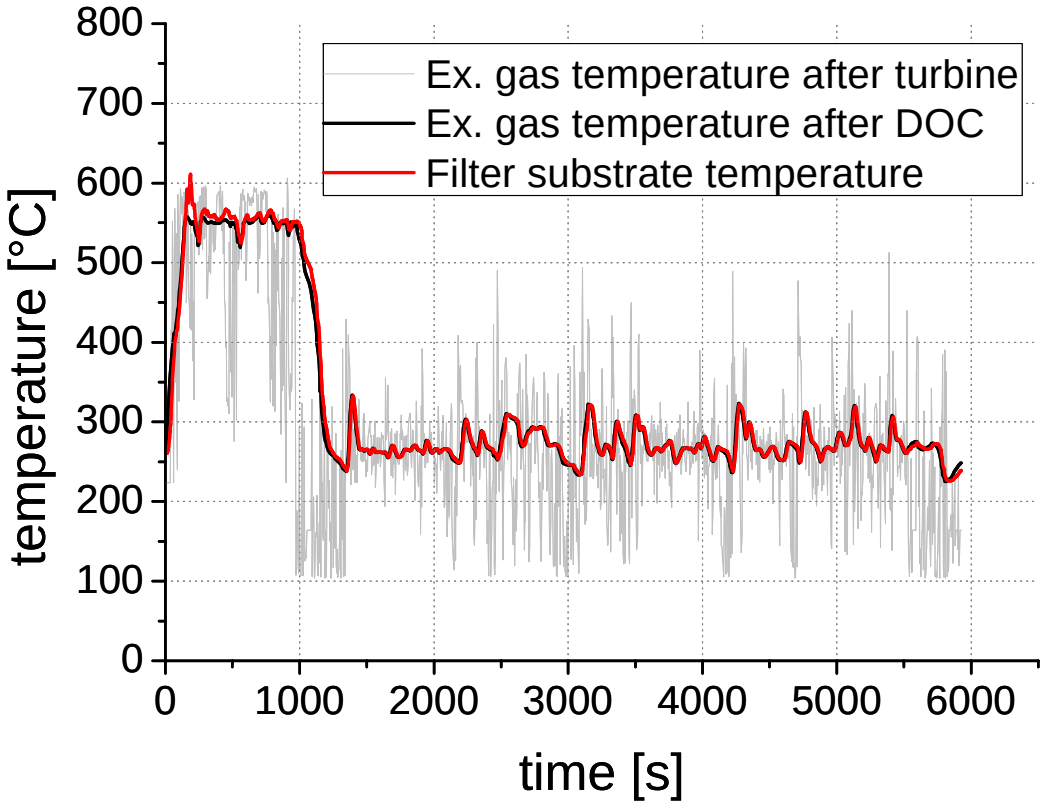
Temperature profiles during regeneration under the highway cycle



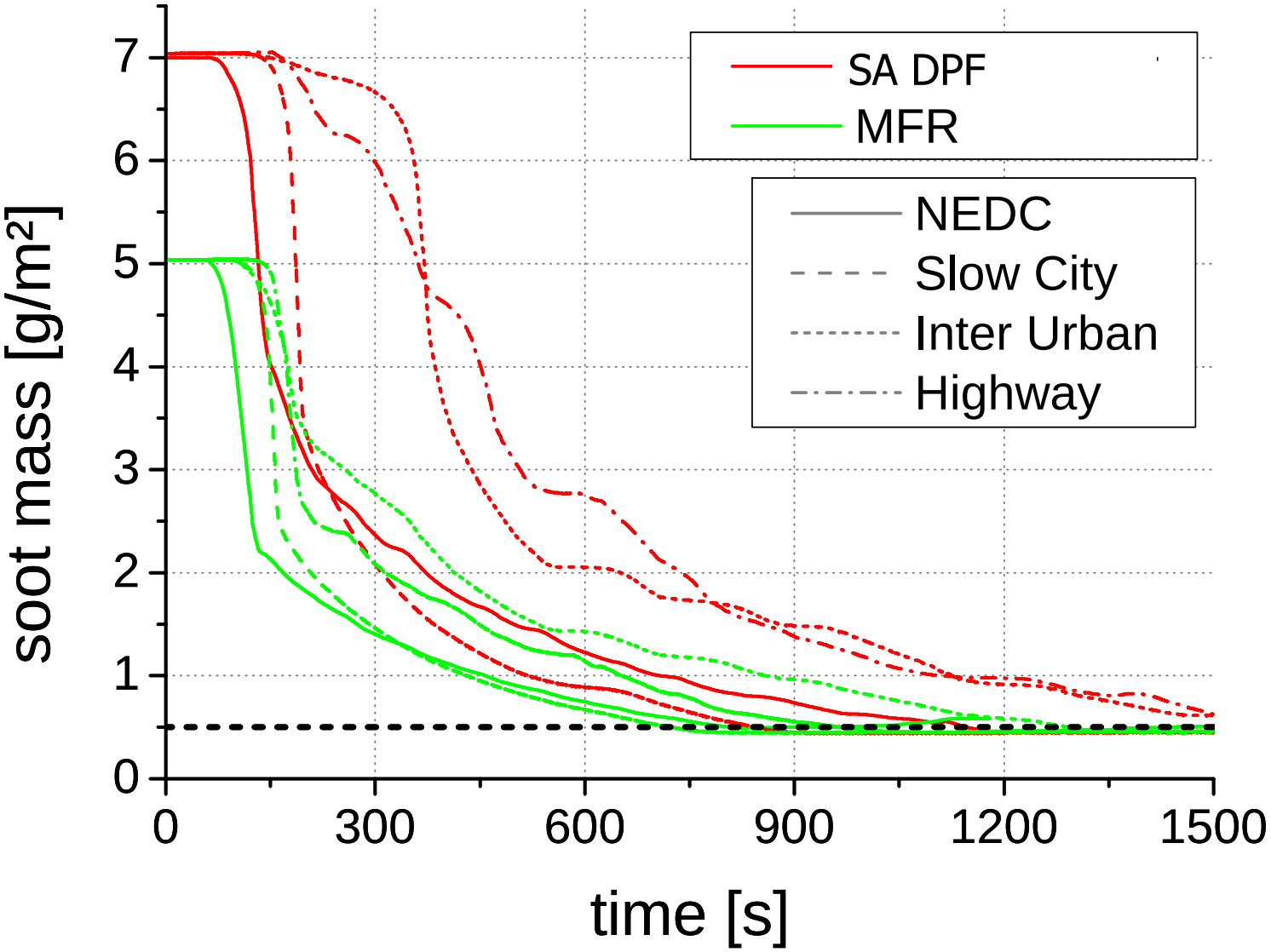
SA DPF



MFR

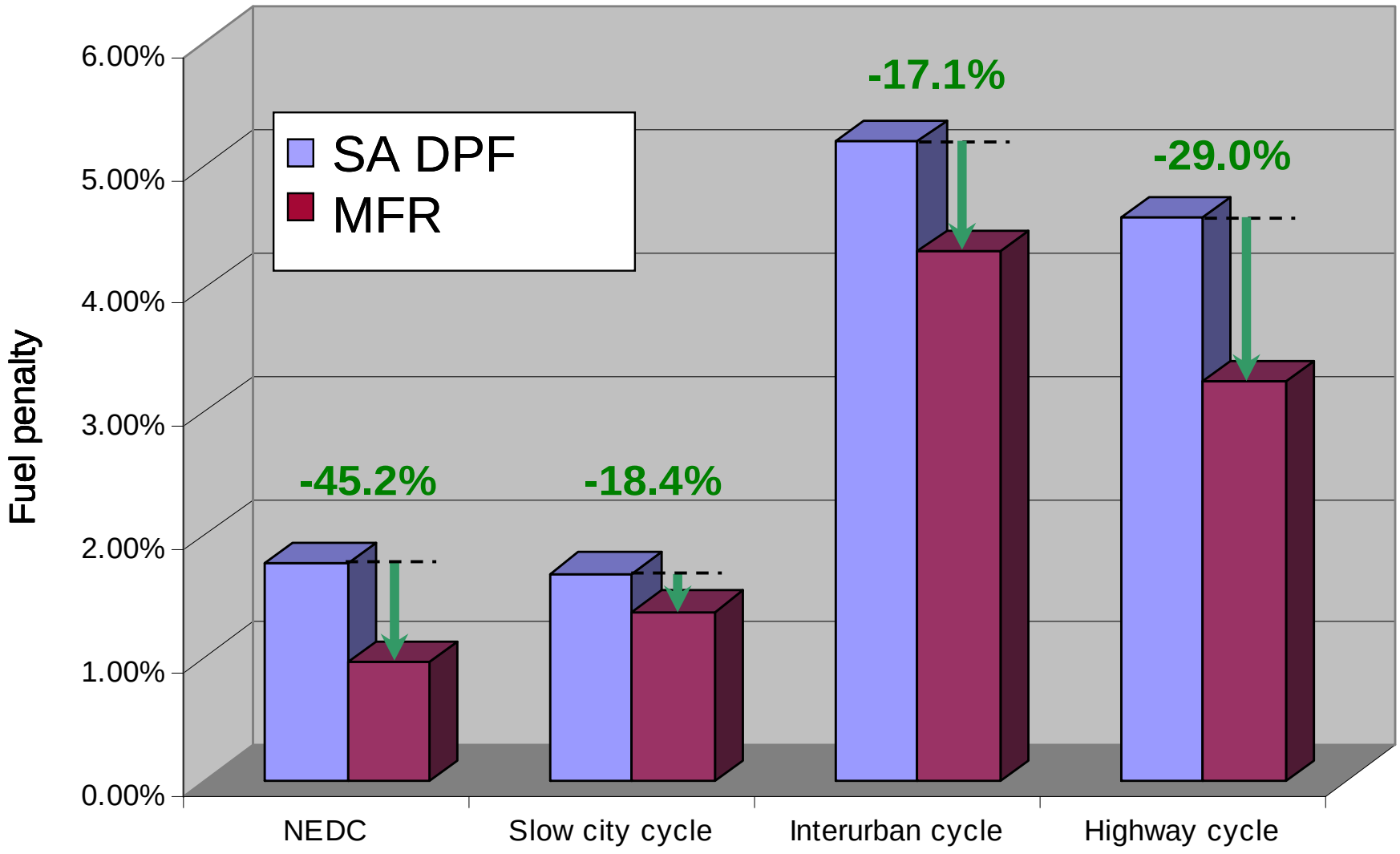


Evolution of soot mass during regeneration



MFR consistently achieved much shorter regeneration interval on all driving cycles/patterns considered.

Fuel penalty due to filter regeneration for different driving cycles



Conclusions (1)

- A Diesel exhaust emission control device termed Multi-Functional Reactor (MFR) was realized **combining filtration, internal heat recovery, soot and gas oxidation** functions.
- **Aging** of the MFR did not result in losses in its catalytic activity and filtration efficiency. An increase in the filter pressure drop by nearly 20% mainly due to ash particles accumulation.
- The MFR has equivalent **performance** under both conventional and HCCI engine operation conditions with respect to filter pressure drop and regeneration performance.

Conclusions (2)

- Simulation results indicated significant **economy on the fuel consumption** related to benchmark DPF operation (47% in the NEDC).
- **HCCI soot** exhibited:
  - increased H_2 content and is oxidized more easily in TGA conditions,
  - differences in primary particle morphology (core/shell particles),
  - no significant differences in the degree of structural organization, as revealed by Raman spectra analysis,
  - equivalent soot cake microstructural properties evolved at either conventional or alternative combustion conditions.
- The catalyst soot oxidation activity was not affected by the applied combustion type and the possible differences recognized by TEM and TGA analysis did not seem to result in any performance differences at the catalyzed monolith scale.

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Thank you for your attention!

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