GPF model-based optimization methodologies supporting RDE conformity

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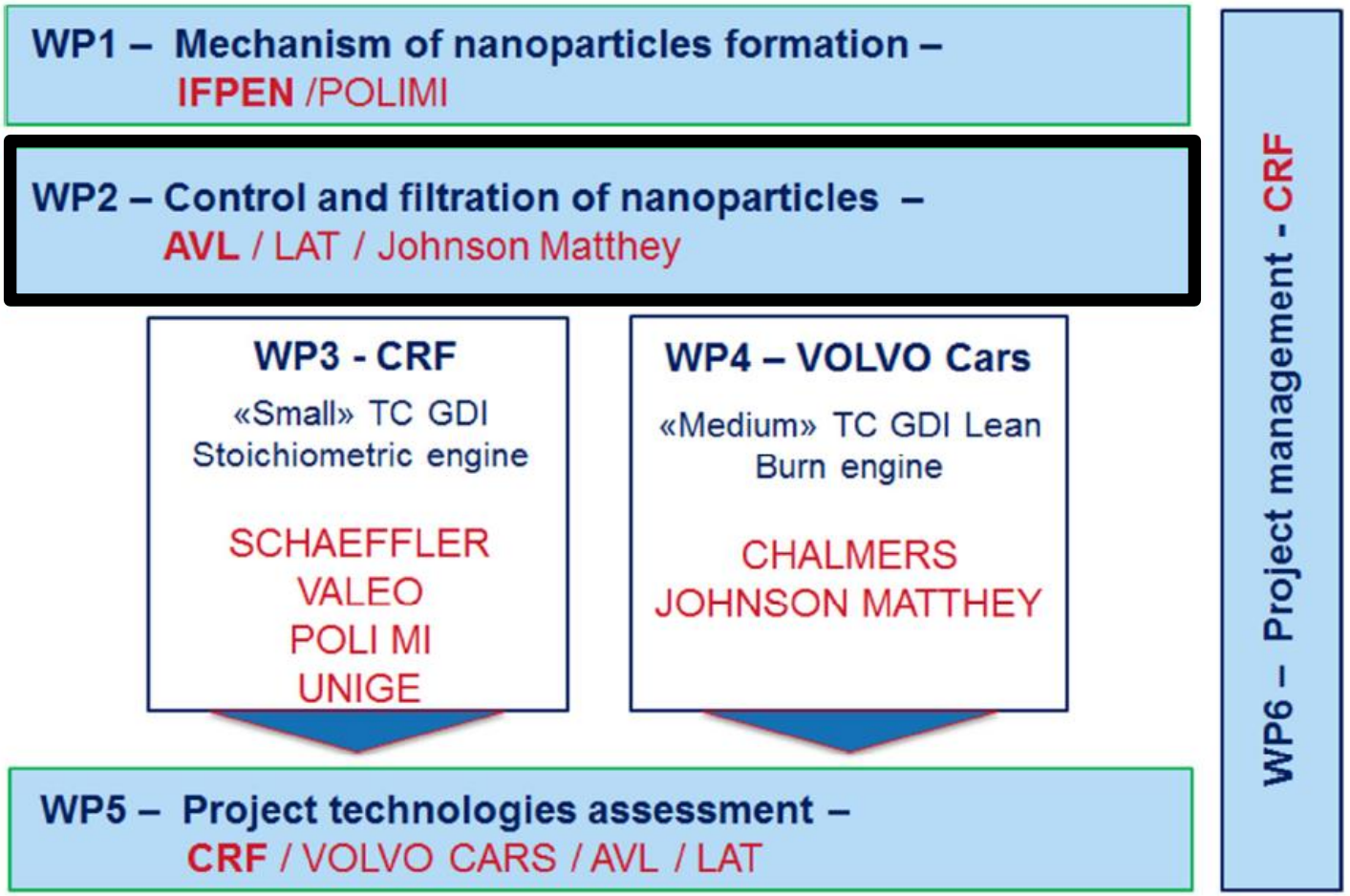
UPGRADE project structure



Motivation

Ultra-clean gasoline engines via (c)GPF & Exhaust After Treatment (EAT) system optimization

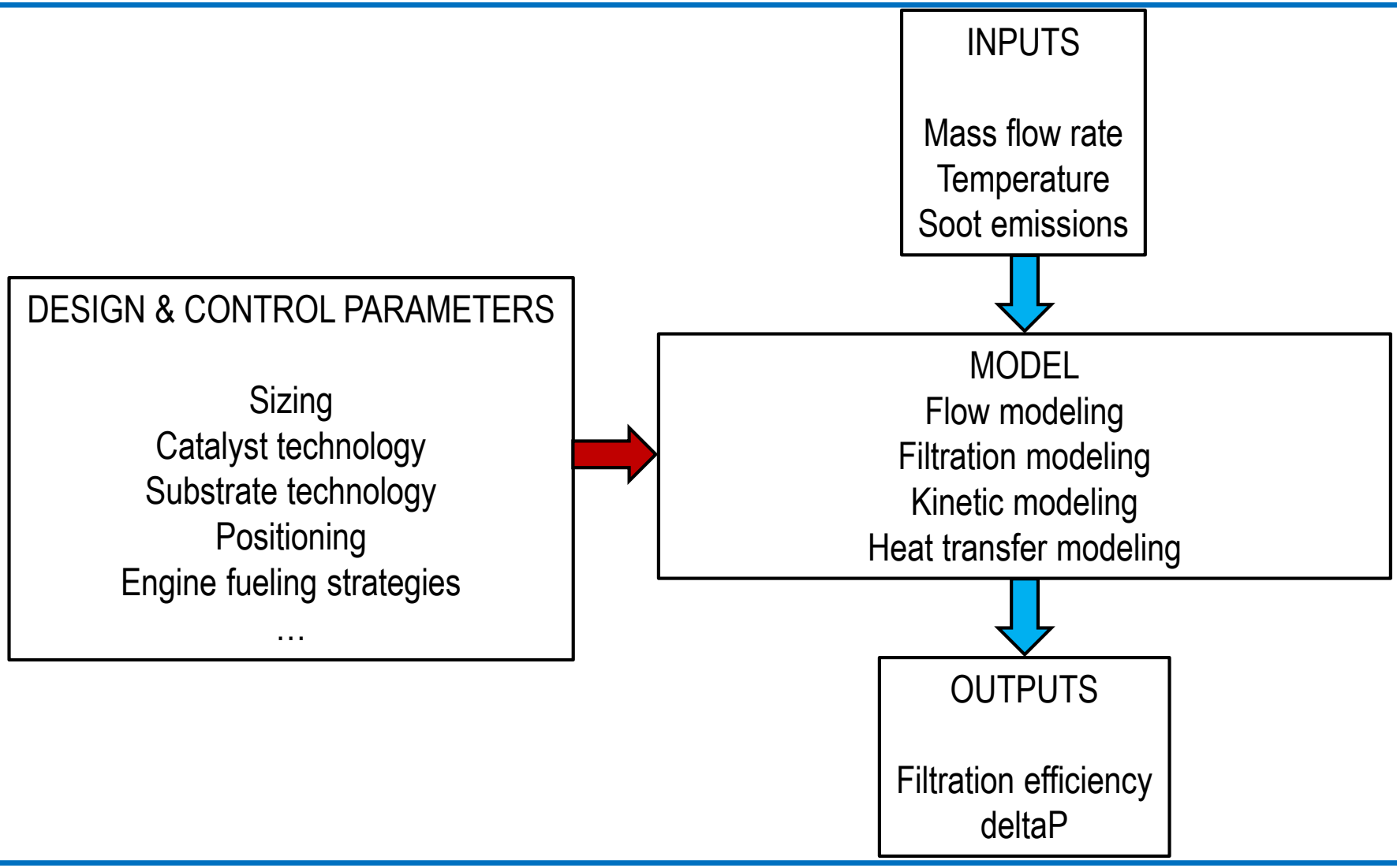
In this respect:

- 13 (c)GPFs of different cell- and wall micro-structure were tested

Filter	D x L [mm]	Material	Wall thickness [mils] / Cell density [cpsi]	Mean pore size (MPS) / Porosity (P)	Washcoat loading [g/l]
11	118 x 127	Cordierite	6 / 220	Small / Low (Indicatively: 10µm / 45%)	0
5			5 / 360		
10			8 / 200	Small / Medium (Indicatively: 10µm / 55%)	
3			9 / 240	Large / High (Indicatively: 20µm / 65%)	0 / 50
6			8 / 300		
8			10 / 300		
1			12 / 300		
A	118 x 114		8 / 300		100
B					50

- Based on the test results, predictive deltaP and filtration models were developed

Model
Inputs / outputs



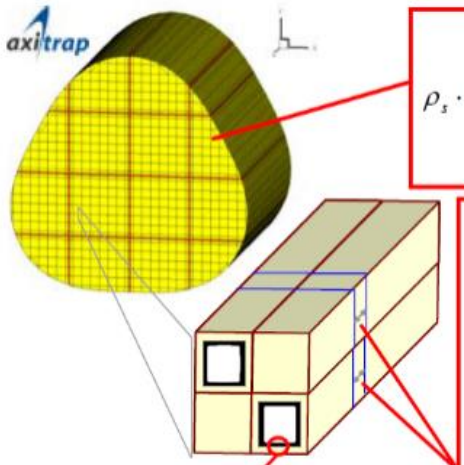
Model
Tunable parameters

deltaP model

- Soot-free wall permeability
- Soot loaded wall permeability
- Soot cake permeability

Filtration model

- Diffusion coefficient
- Interception coefficient
- Gradient coefficient



Filter scale: 3-d solid energy balance

$$\rho_s \cdot C_{p,s} \frac{\partial T_s}{\partial t} = k_{s,x} \frac{\partial^2 T_s}{\partial x^2} + k_{s,y} \frac{\partial^2 T_s}{\partial y^2} + k_{s,z} \frac{\partial^2 T_s}{\partial z^2} + S$$

$$S = H_{conv} + H_{wall} + H_{react} + H_{rad}$$

Channel scale: gas balances
Mass/momentum/energy/species

$$\frac{\partial}{\partial z}\left(d_i^{\,2} \rho_i v_i\right) = (-1)^i 4 d \rho_w v_w$$

$$\frac{\partial p_i}{\partial z} + \frac{\partial}{\partial z}\left(\rho_i v_i^2\right) = -\alpha_1 \mu v_i / d_i^{\,2}$$

$$C_{p,g} \rho_1 v_1 \Big|_z \frac{\partial T_1}{\partial z} = h_1 \frac{4}{d_1}\left(T_s - T_1\right)$$

$$C_{p,g} \rho_2 v_2 \Big|_z \frac{\partial T_2}{\partial z} = \left(h_2 + C_{p,g} \rho_w v_w\right) \frac{4}{d}\left(T_s - T_2\right)$$

$$\frac{\partial}{\partial z}\left(v_1 y_{1,j}\right) = -\frac{1}{df_{-w}^{\,2}} v_w y_{1,j} + \frac{1}{df_{-w}} k_{1,j}\left(y_{1s,j} - y_{1,j}\right)$$

$$\frac{\partial}{\partial z}\left(v_2 y_{2,j}\right) = \frac{1}{df_{w_s}^{\,2}} v_w y_{2s,j} + \frac{1}{df_{w_s}} k_{2,j}\left(y_{2s,j} - y_{2,j}\right)$$

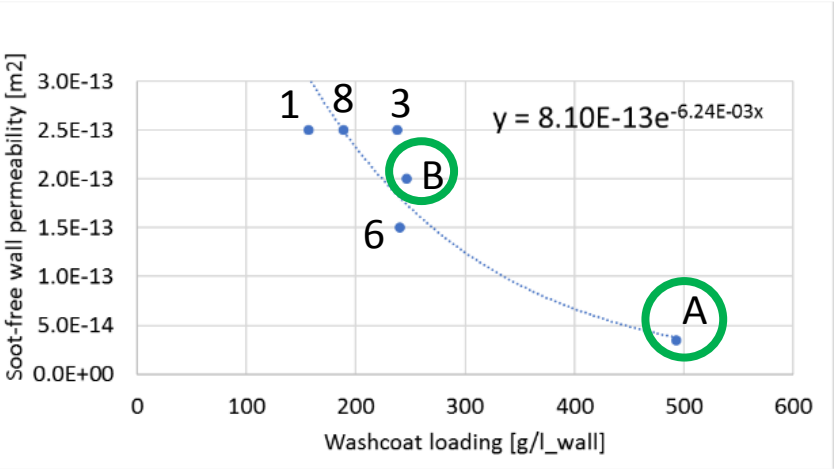
Wall/soot scale balances
Momentum/soot/ species

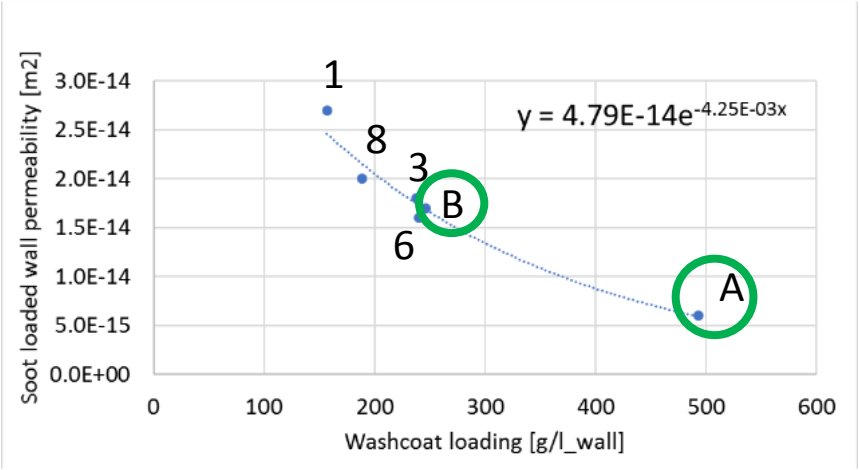
$$\frac{dp}{dx} = \frac{\mu v(x)}{k_p}$$

$$\frac{d\hat{m}_p}{dt} = -\hat{m}_p \sum R'_k + s_F \rho_w v_w \mu_p$$

$$v_w \frac{\partial y_j}{\partial x} - D_j \frac{\partial}{\partial x}\left(f_x \frac{\partial y_j}{\partial x}\right) = \frac{f_x}{c_m} \sum_k c_{j,k} R_k$$

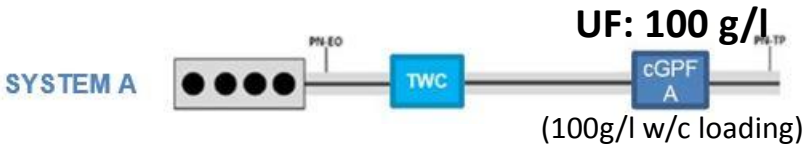
Predictive flow resistance tool as a function of wall micro-structure

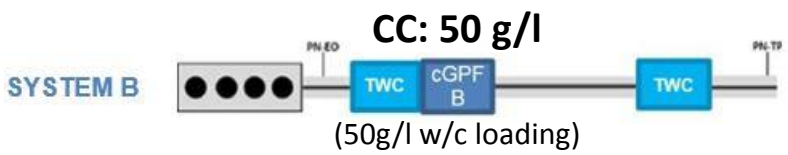


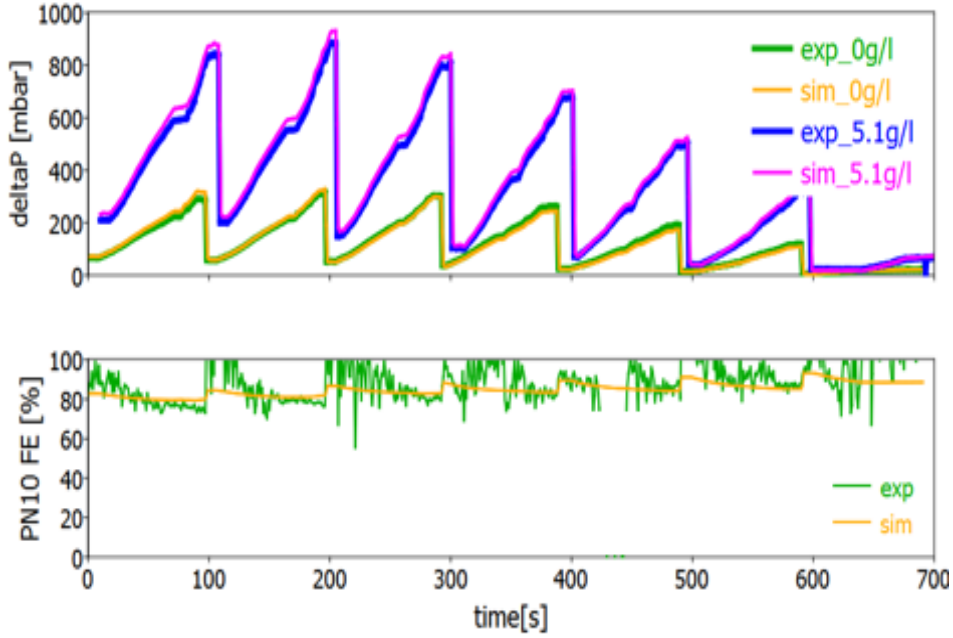


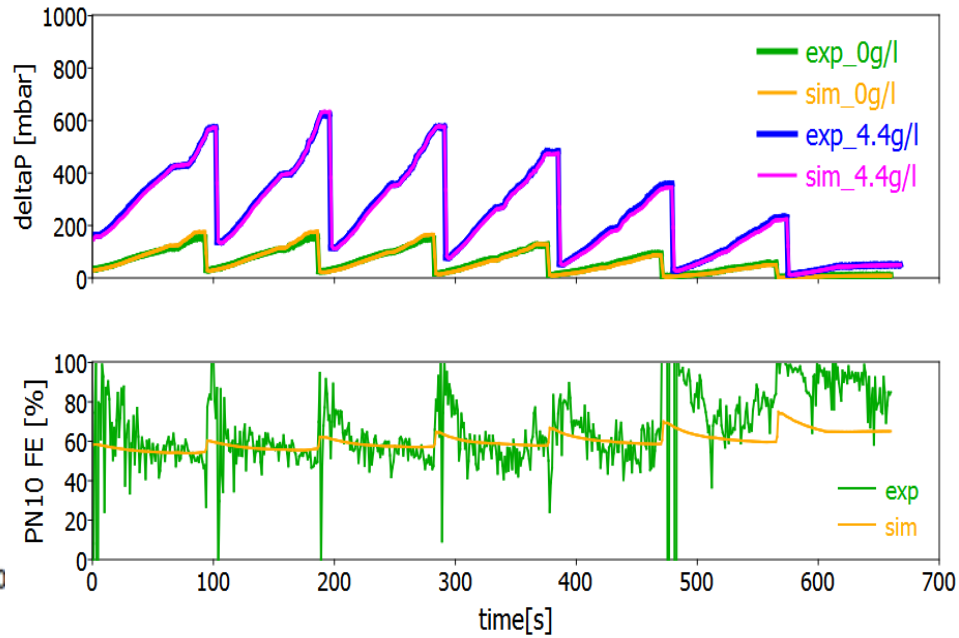
GPF A (UF: 100g/l) and B (CC: 50g/l)
deltaP and filtration performance investigation

deltaP & filtration efficiency prediction for cGPF A and cGPF B



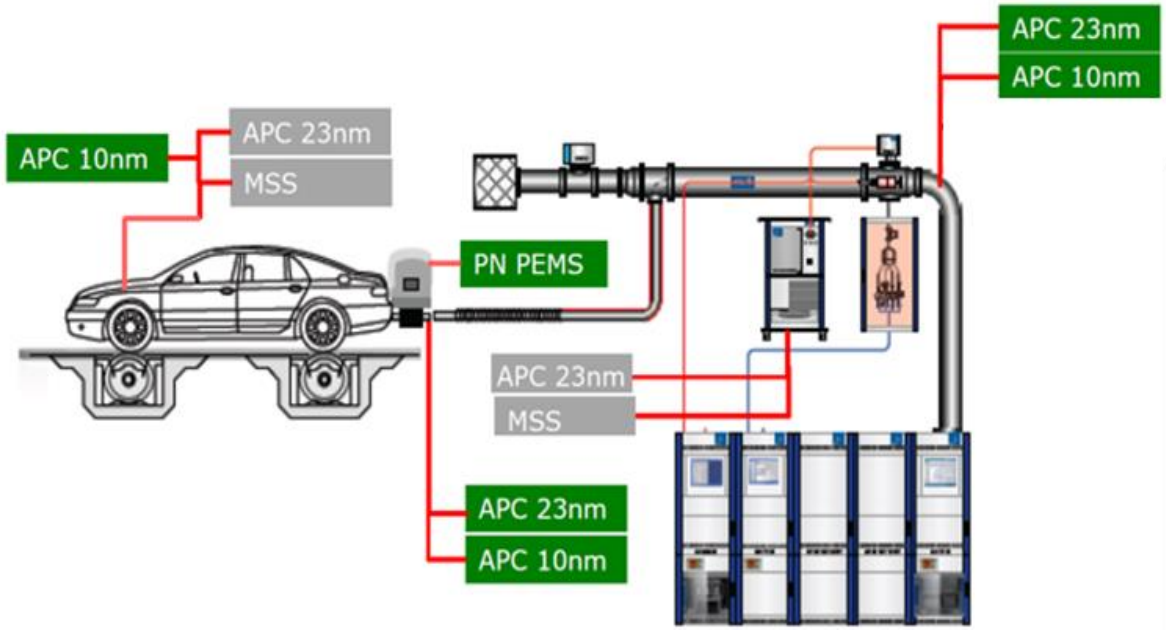






- Experimental & simulation deltaP and filtration efficiency results.
- SYSTEM B has better deltaP and worse filtration performance compared to SYSTEM A due to its higher effective porosity.

Model validation by driving cycle tests



The original exhaust system was removed and replaced with exhaust systems of two different variants:

UF: 100 g/l

(100g/l w/c loading)

CC: 50 g/l

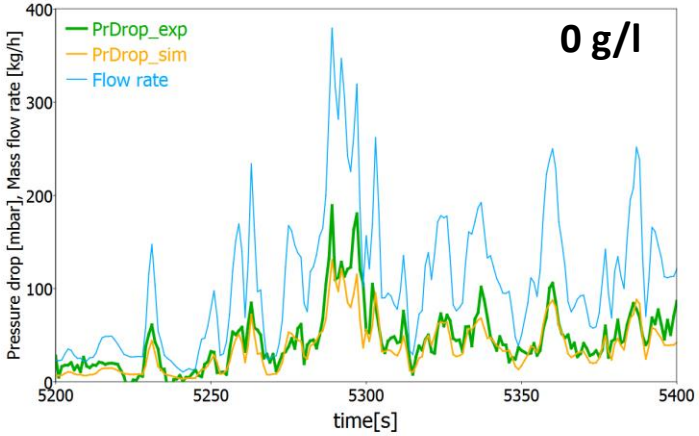
(50g/l w/c loading)

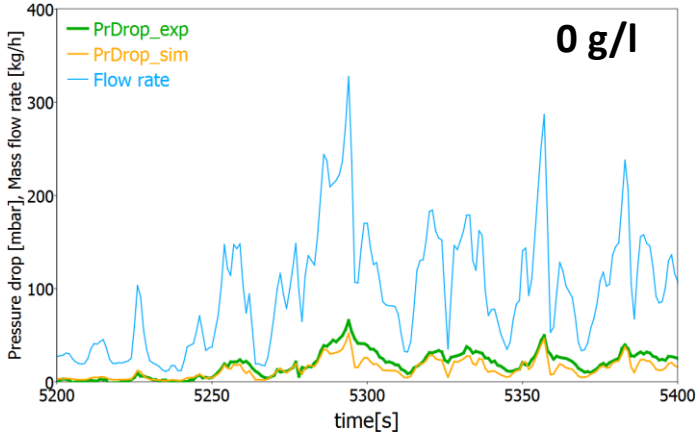
deltaP model validation
RDE aggressive test cycles

UF: 100 g/l

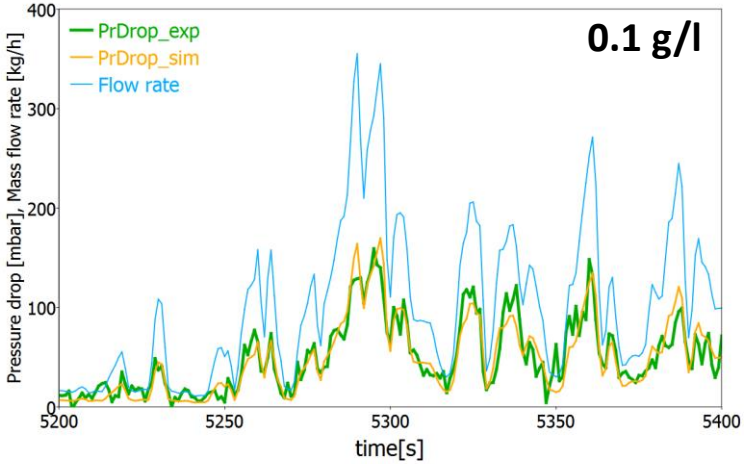
CC: 50 g/l

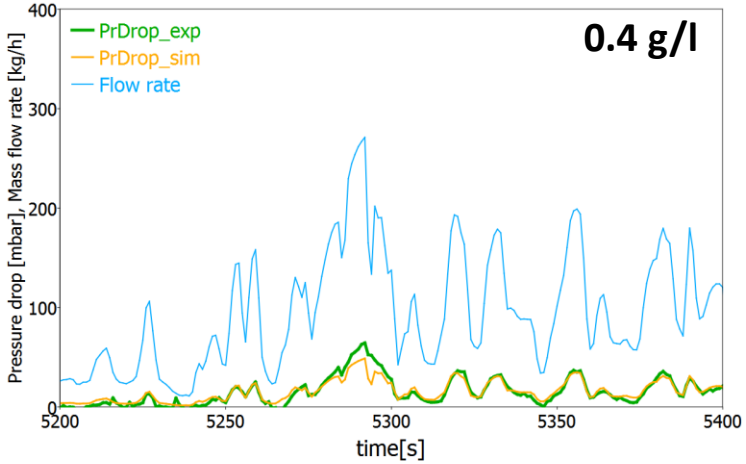
Soot-free initial state





Soot loaded initial state

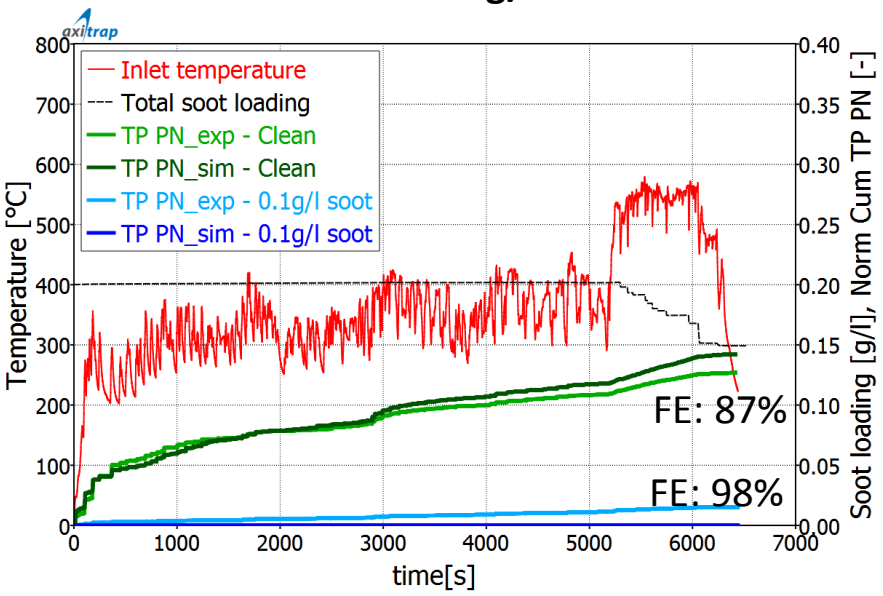




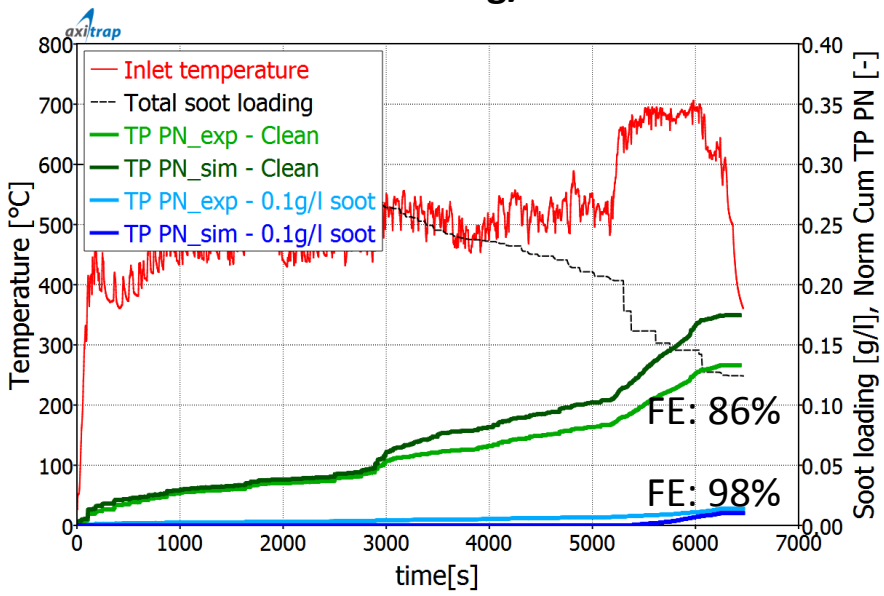
The model is able to accurately predict deltaP for filters at both soot-free and soot loaded conditions

Effect of soot loading on filtration performance
RDE moderate test cycle

UF: 100 g/l

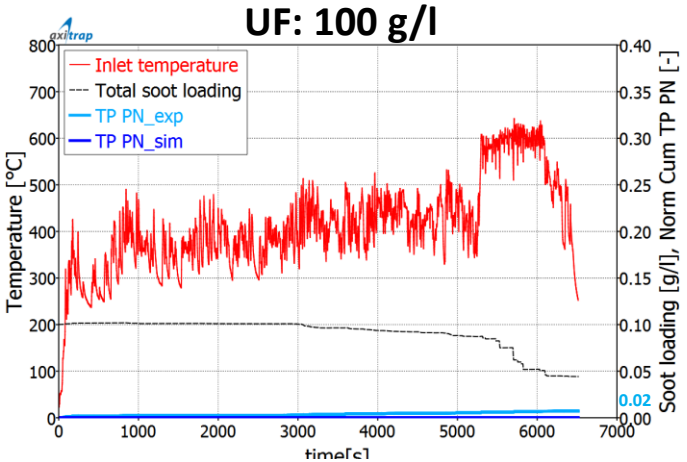


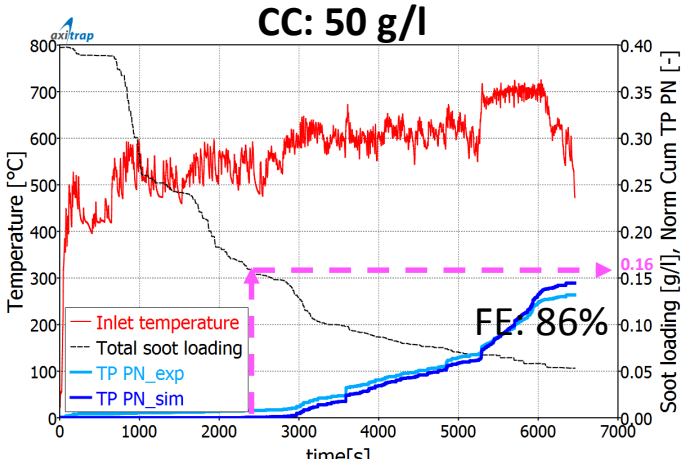
CC: 50 g/l

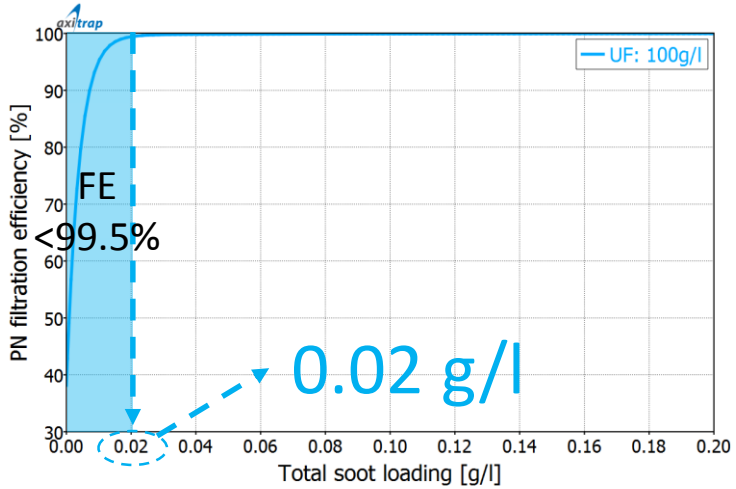


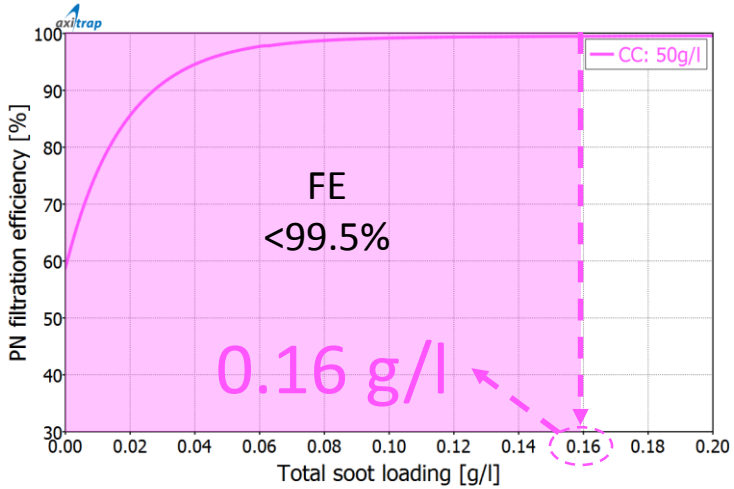
- ~500°C appears to be the threshold above which soot oxidation takes place
- The model is able to predict the significant effect of soot accumulation on a GPF's filtration performance

Effect of cGPF placement on filtration performance
RDE aggressive test cycle









CC 50 g/l GPF regenerates faster due to higher temperature

➔ soot mass drops below 100% FE threshold level

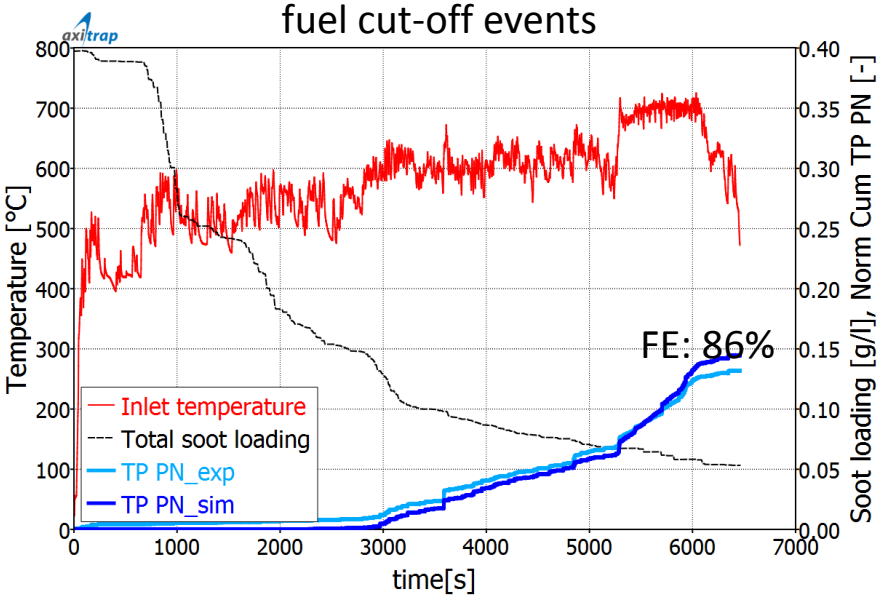
FE: Filtration Efficiency

Validation of model explanation with FCOff deactivation RDE aggressive test cycle

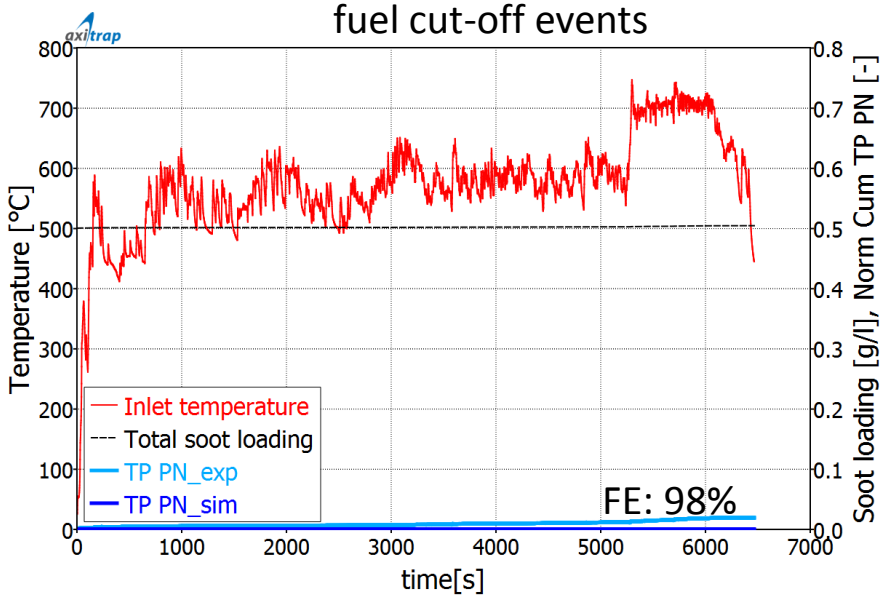
To validate that the CC filter deteriorated filtration performance is associated to its enhanced passive regeneration capability, the test was repeated de-activating fuel cut-off events to limit passive regeneration

CC: 50 g/l

with
fuel cut-off events



without
fuel cut-off events



By deactivation of fuel-cut off mode the GPF retains its high filtration efficiency

FCOff: Fuel Cut-Off

Conclusions

- Soot loading has an important beneficial effect to maintain RDE compliance w.r.t. filtration efficiency.

  ➔Careful management of the regeneration events desirable to avoid complete regenerations

- Multitude of exhaust line design parameters, such as:
  - filter positioning (affecting temperature levels)
  - washcoat amount (affecting filtration performance)
  - engine fueling strategies

  create a very demanding optimization problem.

  ➔ Employment of model-based methodologies can reduce development efforts and associated costs

Thank you very much!