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SOOT MODEL FOR DPF MONITORING OVER TRANSIENT ENGINE OPERATIONS

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ABSTRACT

Diesel particulate filters (DPFs) are recognized as the most efficient technology for particulate matter (PM) reduction, with filtration efficiencies in excess of 90%. Design guidelines for DPFs typically are: high removal efficiency, low pressure drop, high durability and capacity to resist high temperature excursions during regeneration events. The collected mass inside the trap needs to be periodically oxidized to regenerate the DPF. Thus, an in-depth understanding of filtration and regeneration mechanisms, together with the ability of predicting actual DPF conditions, could play a key role in optimizing the duration and number of regeneration events in case of active DPFs .

Thus, the correct estimation of soot loading during operation is imperative for effectively controlling the whole engine-DPF assembly and simultaneously avoiding any system failure due to a malfunctioning DPF. A viable way to solve this problem is to use DPF models. This paper addresses real-time DPF modeling issues with special regard to key parameter settings, by using the 1D code ExhAUST (Exhaust Aftertreatment Unified Simulation Tool), developed jointly by the University of Rome Tor Vergata and West Virginia University. ExhAUST is characterized by a novel and unique full analytical treatment of the wall, and it is capable of following the evolution of DPFs loading conditions over time in both steady state and transient operations without any change in model calibration. Moreover a novel and original procedure called "virtual conditioning" has been developed to set the initial condition of the code as representative of the physical state of the DPF.

Real-time models can be used to address challenges posed by advanced control systems, such as the integration of the DPF with the engine or other critical aftertreatment components (such as Diesel NOx control components), or to develop model-based OBD sensors. One of the major issues in such applications is the accurate estimation of engine Particulate Matter (PM) emissions as a function of time. Such data is required as input data for any kind of model. The problem can be overcome in two ways. The simplest way consists of using PM maps capable of giving an estimation of particulate matter emissions over the whole engine operating domain. On the other hand, an in-line soot sensor may be employed to gather the real transient soot emissions signal, which will serve as an input to the model.

In this paper, ExhAUST has been coupled to a prototype in-line soot sensor currently being investigated at WVU. The in-line soot sensor is ideal for model based control system development, as it is capable of performing continuous measurements directly in the exhaust line with adequate size and accuracy requirements. Experimental data will be completed with particle size distribution, by means of TSI EEPS 3090, to add additional transient information, for the sake of consistency.

EXPERIMENTAL METHOD

The DPF model presented in this work was calibrated on data gathered by testing a Johnson-Matthey CCRT® coupled with a MY2004 Mack® heavy-duty diesel engine equipped with a high-pressure loop exhaust gas recirculation system (EGR) and a variable geometry turbocharger (VGT). Selection of engine modes for loading and regeneration procedures was based on preliminary testing using the 13-mode European Stationary Cycle (ESC) [1]. Because of the relatively low PM emissions of the MY2004 an engine point characterized by low exhaust temperature was needed in order to limit the continuous regeneration rate at low temperature given mainly by NO_2. Initially the engine point characterized by 25% load and rated speed (R25) was selected from the ESC 13 modes as suitable for the filter loading process. However it turned out that the exhaust temperature (close to 280 C) was too high to obtain a continuous loading process since the system reached the equilibrium point. Hence the 10% load at rated speed (R10) was chosen as suitable loading cycle given the lower exhaust temperature and lower NO_x emissions. The engine point used as filter regeneration cycle was the full load at rated speed (R100) from the ESC. Since the DOC/DPF was an already used system the testing procedure was started by operating the engine at the R100 mode until an equilibrium condition for the DPF was reached (1.5 hrs). Thereafter the engine was run for almost 25hrs on the loading cycle (R10) only intermitted by periodic DPF weigh measurements and refueling pauses every 4 hrs. Before regenerating the filter by running the engine at R100 mode, two Federal Test Procedure (FTP) were run [2]. Combination of steady state and transient cycles was adopted in this work in order to stress the model in tracking filter loading status over totally different thermodynamic conditions.

MODEL TUNING AND RESULTS

Since the CCRT used in this study was an already used system, coherent initial condition needed to be imposed to the model. To that aim a novel procedure named "Virtual Conditioning" was performed to naturally tune the model by simulating a random sequence of loading/regeneration cycles until a steady condition during the loading process was observed. The virtualization of the DPF history is primarily important as it allows to correctly represent the hysteresis effect after several loading/regeneration cycles due to ash accumulation and formation of a soot membrane which prevents PM soot from reaching the wall limiting the soot accumulation on the internal surface of the filter channels. Moreover a specific calibration methodology was applied in order to generate a single calibration to be employed in both steady state and transient engine operations.

The loading process is summarized in Figure 1 which shows a comparison between experimental and simulated data for both the first 6 hours and the last 8 hours of the loading procedure [1]. It is worth noting that the transient behavior observable in the first 30 min of each cycle is due to the change in temperature of the filter rather than transition between wall filtration regime and soot layer accumulation regime.

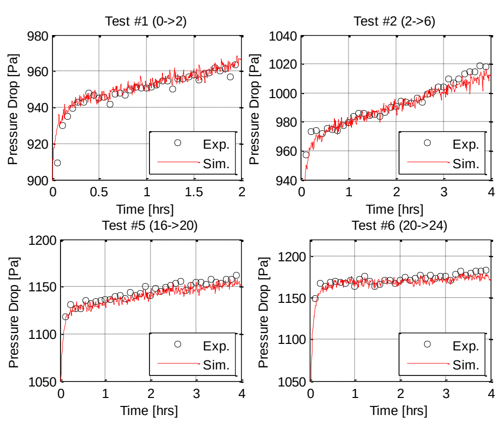

Figure 1: Pressure drop evolution during filter loading.

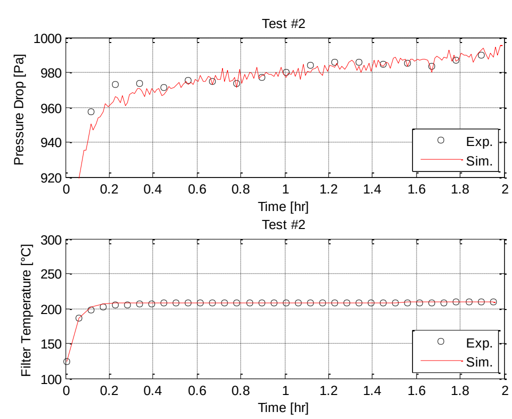

Figure 2: Pressure and Temperature for Test#2

Filter soot loading has been tracked by weighing the filter as commented above. Soot mass trapped during loading procedure shows good agreement with experimental data.

Model tuning constants, such as activation energies, were kept constant over the entire set of experiments thus suggesting the possibility to employee the presented DPF model to track the soot loading over transient operations. To verify the goodness of the predictions, the model was applied to reproduce the behavior of the filter during two consecutive transient cycles run at the end of the R10 modes but before the R100. Comparison between simulated and experimental values is given in Figure 3.

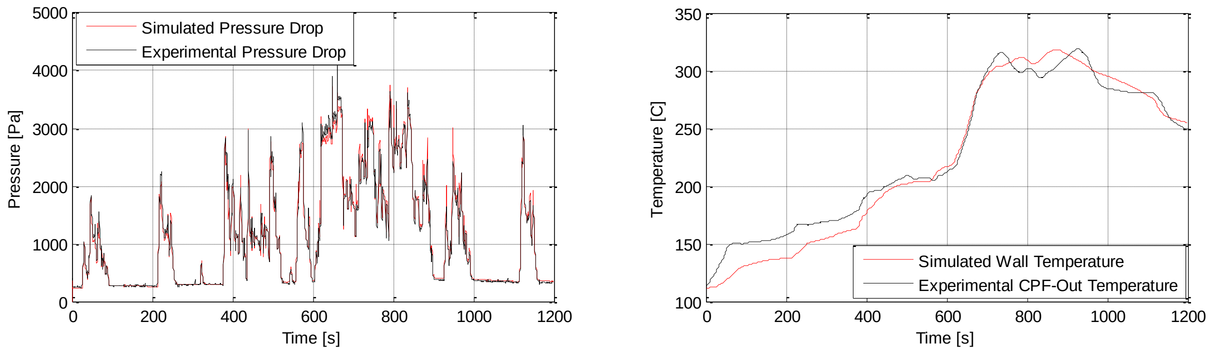

Figure 3: Pressure drop and filter temperature over the FTP cycle. Simulated vs experimental values.

By analysis of figures 1 to 3 it may be concluded that the presented model correctly captures the evolution of the DPF properties associated with soot loading process and continuous regeneration at low temperature by NO_2 means occurring over both the R10 steady state modes and FTP transient cycle.

In order to verify the accuracy of the model to simulate soot oxidation at high temperature, simulations of the R100 mode were carried out as final test after the two transient modes presented above. Figure 4 shows the results obtained for the R100 engine mode.

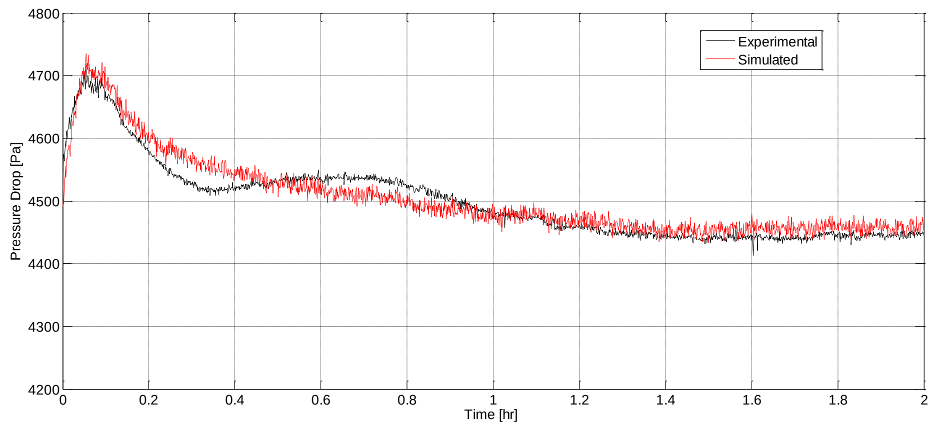

Figure 4: Pressure drop over the R100 mode. Simulated vs experimental values.

The reader may refer to Cozzolini et al. [1] for complete model validation and Mulone et al.[2] for complete analysis of results associated with transient operation.

Concluding, the presented model was capable of tracking filter loading status over almost 30 hr of continuous operation. Good agreement with experimental data over both steady state and transient engine operating conditions was assured by the novel calibration methodology developed to fit experimental data of different tests without any change in tuning parameters. Integration with Pegasor soot sensor [3] was fundamental to acquire detailed information about PM concentration entering the CCRT, especially over transient engine operations where emissions maps lack of accuracy thus leading to wrong estimation of needed input data.

References

1. Cozzolini, A., Mulone, V., Abeyratne, P., Littera,D., Gautam, M., "Advanced Modeling of Diesel Particulate Filters to Predict Soot Accumulation and Pressure Drop", SAE Technical Paper, 2011-24- 0187, Internal Combustion Engine Congress Capri, Italy, September 2011. (Accepted for Publication).
2. Mulone V., Cozzolini A., Abeyratne P., Besch M.C., Littera D., Gautam M., “ExhAUST: DPF Model for Real-Time Applications”, SAE Technical Paper, 2011-24- 0183, Internal Combustion Engine Congress Capri, Italy, September 2011. (Accepted for Publication).
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Soot Model for DPF Monitoring Over Transient Engine Operations

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Outline

- Background
- Objectives
- DPF model review
- Experimental Setup
- Model Validation
  - Steady State
  - Transient
- Conclusions

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Background

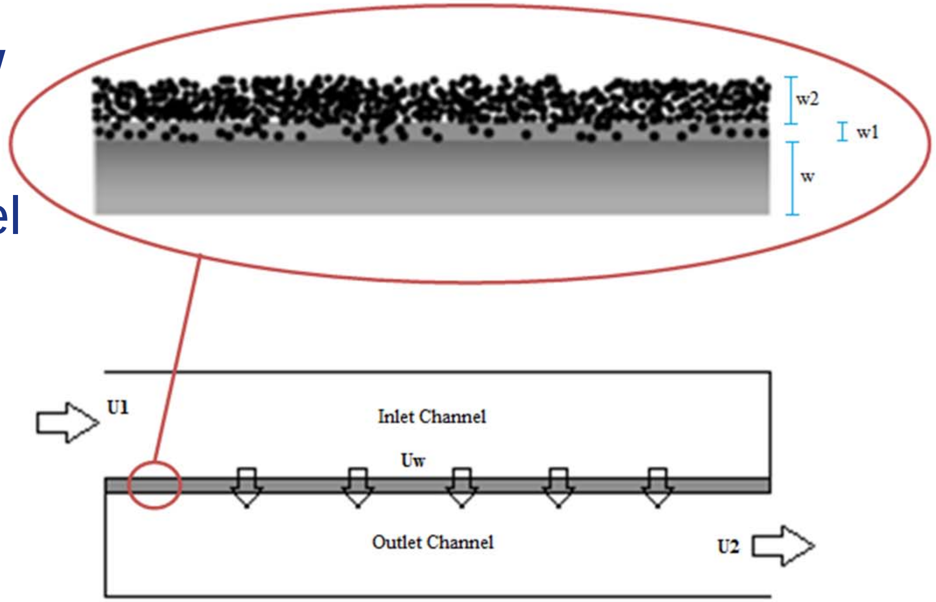
- Stringent standards for PM emissions require the use of Diesel Particulate Filters (DPF)
- DPF diagnostics and control strategies
  - Excessive backpressure: high fuel consumption, high emission levels, engine/DPF failures
  - Regeneration events set up: nanoparticle emissions due to carbon oxidation and lower DPF filtration efficiency

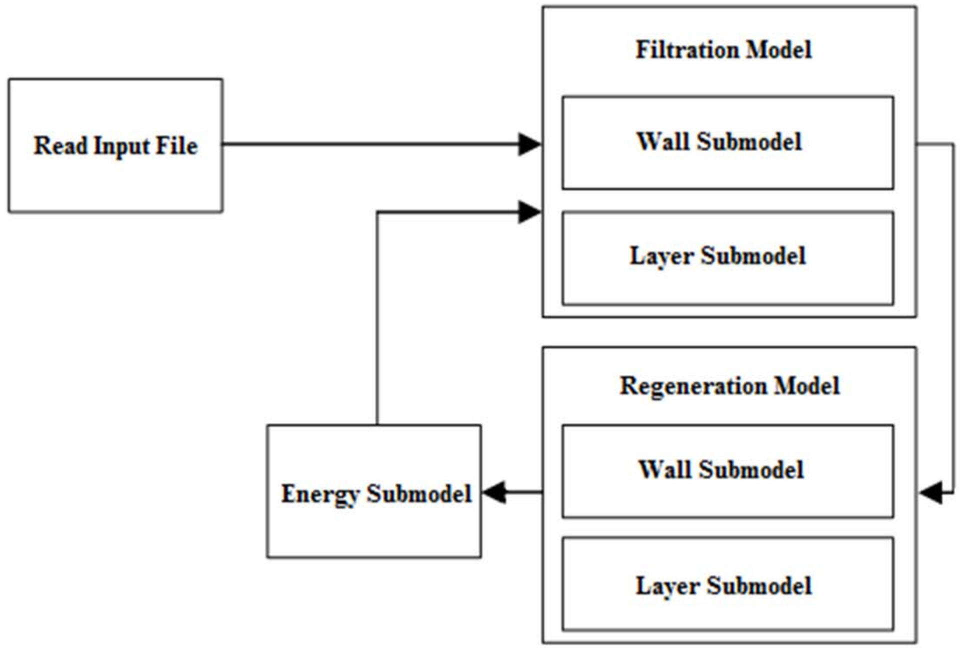
Objectives

- To build a unified code capable of virtually replicating most aftertreatment devices
- To define a model calibration methodology for predicting dynamic behavior of aged systems using constant tuning parameters
- To use DPF model outputs to define possible DPF regeneration strategies

Model Review

- Single inlet-outlet channel
- Three different layers
  - Wall (w)
  - Washcoat (w1)
  - Cake (w2)
- Main submodels
  - Filtration
  - Regeneration
  - Energy
- Unit Collector Theory
- Constant density layer
- Thermal and catalytic assisted regeneration





Model Review: Filtration

$$\begin{cases} \dfrac{dN_i}{dx} = -f_i(x) * N_i(x) \\ f_i(x) = \dfrac{3}{2} \dfrac{\eta_{DR}^i(x)[(1 - e(x))]}{d_C(x)\, e(x)} \end{cases}$$

Polynomial Function n*[th] *Order

$$N_i(x) = N_i^0 \cdot e^{-f_i \cdot x}$$

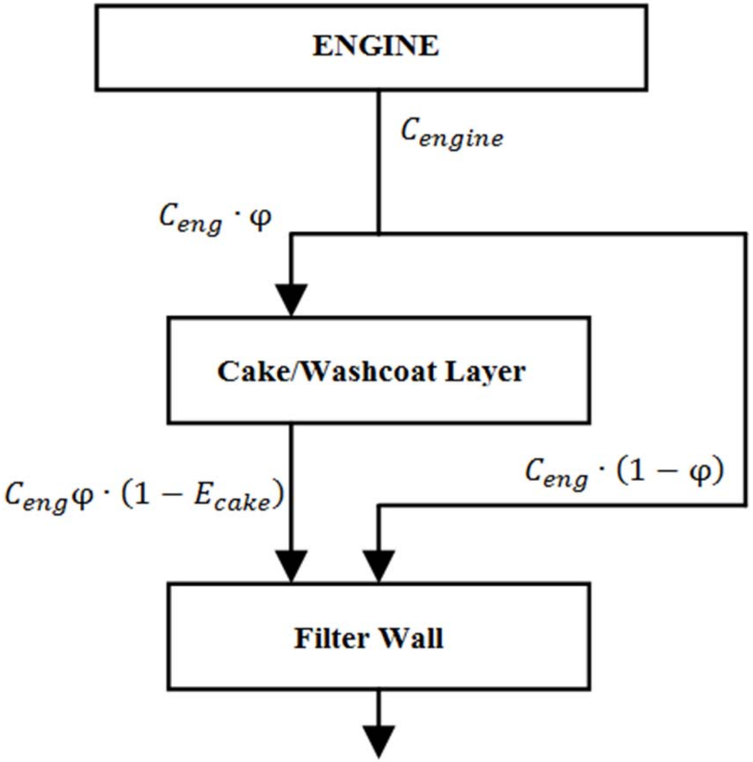
Clean Filter Case

$$N_i(x) = N_i^0 \cdot e^{-\int_0^x f_i(x)dx}$$

Loaded Filter Case

$$N_i^0 = (1 - \varphi(0,t)) \cdot N_i^{DOC\_OUT}$$

Number Conc. at Channel Inlet



$$\eta(x)_{mass} = \frac{\sum_{i=1}^{32} \eta_{DR}(x) \cdot N_i(x) \cdot dlogD_p \cdot D_i^3}{\sum_{i=1}^{32} N_i(x) \cdot dlogD_p \cdot D_i^3}$$

Mass Based Collection Factor

$$\frac{dC(x)}{dx} = -f_{mass}(x) \cdot C(x)$$

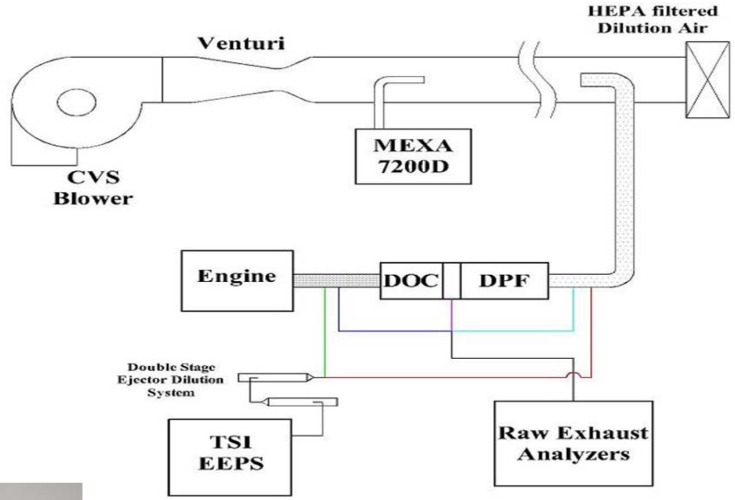
PM mass concentration entering the DPF

Experimental Setup

- Engine testing performed at WVU
- Diluted gas sampled using the Horiba Mexa 7200D
- Complete particle analysis

  performed with TSI-EEPS and Pegasor soot sensor
- DPF has been weighed at high

  temperature at the end of each mode



Experimental Setup

Engine manufacturer specifications

Model	MACK MP7-355E
Configuration	6 cylinders, Inline
Aspiration	Sliding Nozzle Variable Turbocharger / Intercooler
Injection System	Dual Solenoid Electronic Unit Injector (EUI)
Maximum Torque	1844 Nm (1360 ft-lbs) @ 1200 RPM
Maximum Power	265 kW (355 bhp) @ 1800 RPM
Displacement, L (cu-in)	11 (659)
Compression Ratio	16.0:1
Bore & Stroke, mm (in)	122.94x151.89 (4.84x5.98)

Characteristics of the J.M. CCRT

Parameter	DOC	DPF
Diameter (in)	12	12
Length (in)	5	12
Cell Density (cpsi)	400	100
Wall Thickness (mil)	4	12
Clean wall porosity	-	0.5

Steady state engine modes characteristics

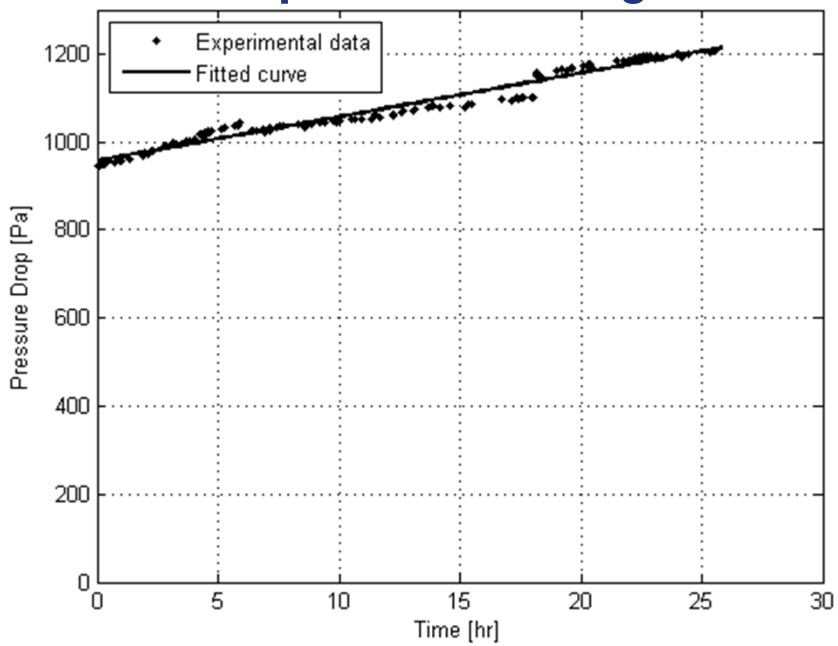
Test Mode	R10	R100
Duration [h]	26	3
Eng. Load [ft-lbf]	105	1018
Eng. Speed [rpm]	1800	1800
Fuel Flow Rate [kg/h]	11.64	56.11
C-CRT Inlet Temp. [C]	226.5	483.8
Intake Air Flow [scfm]	256.4	588.1

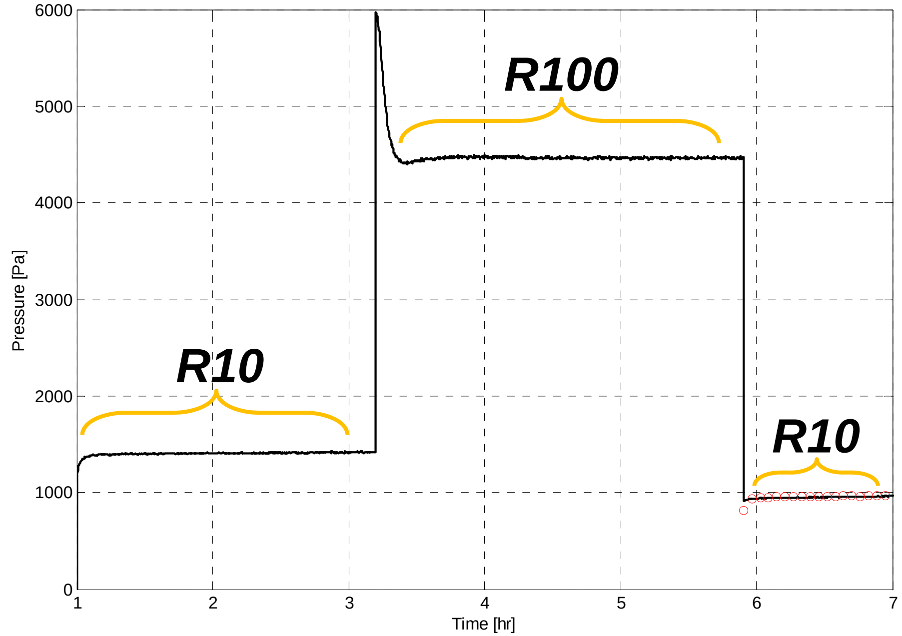
Transient mode: Federal Test Procedure (FTP)

Model Validation

Numerical pre-conditioning procedure:

i) Select a set of tuning variables and perform virtual conditioning
ii) Check the capability of the model to predict experimental values
iii) If the simulated values are out of the confidence interval the process start again from point "i"





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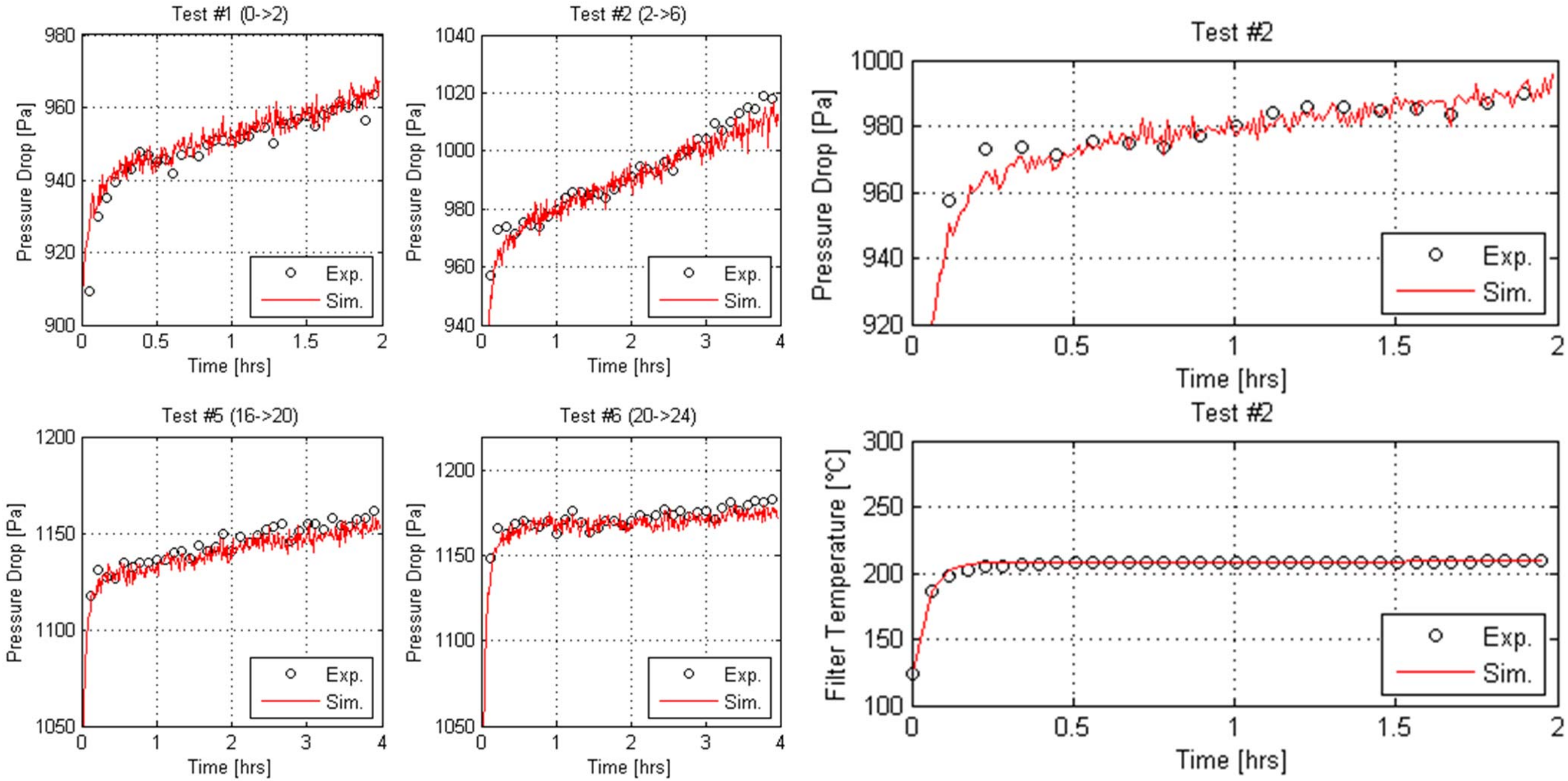
Model Validation

Steady state loading



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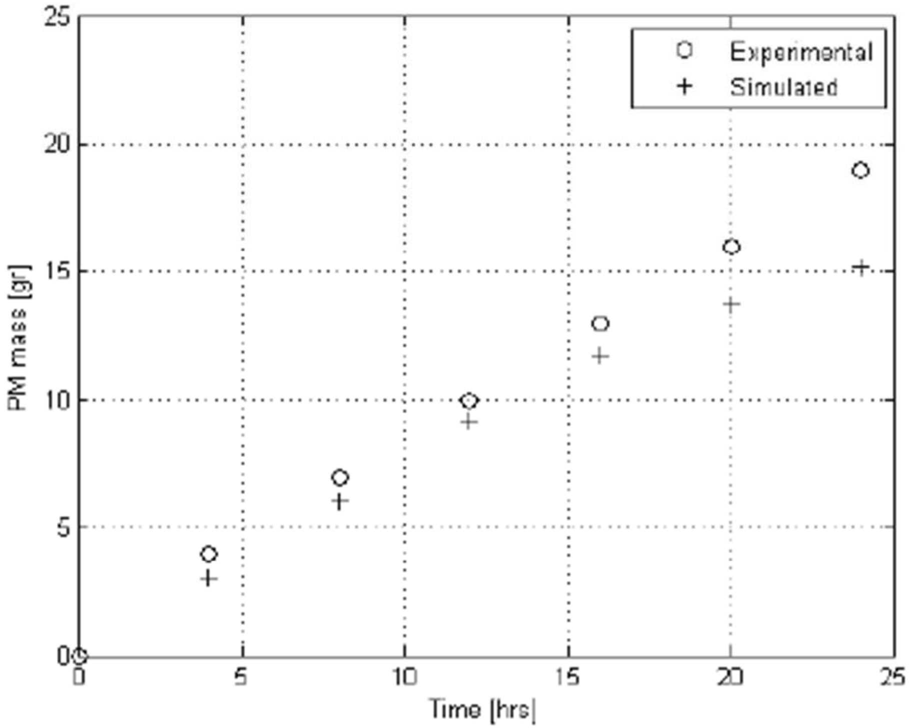
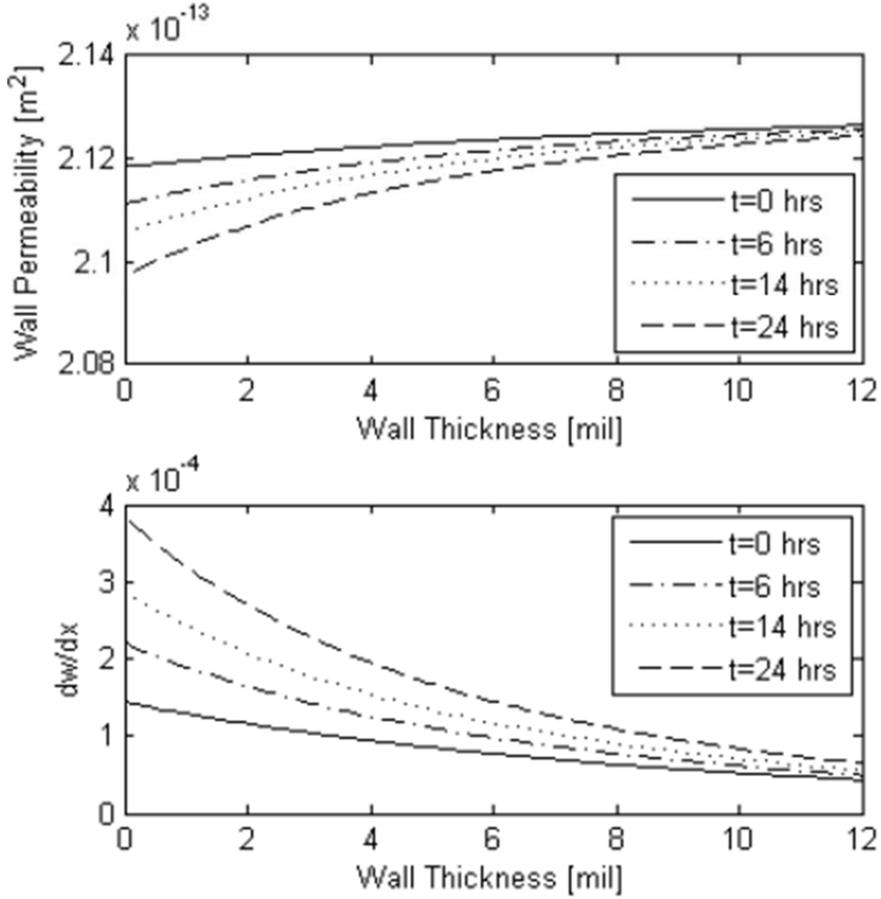
Model Validation

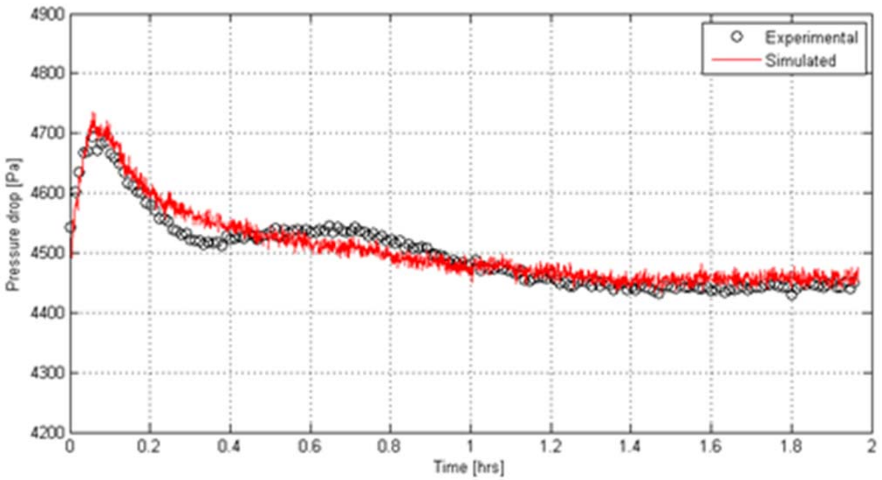
Steady state loading

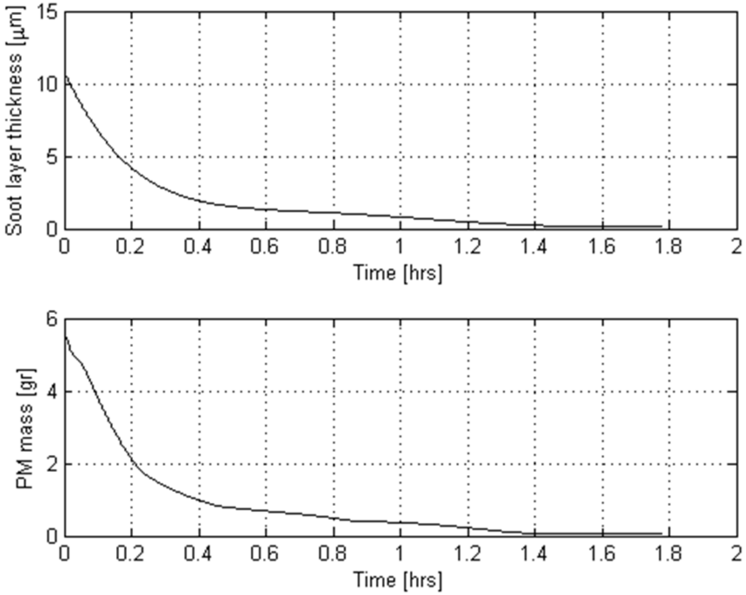




Model Validation

Steady state Regeneration





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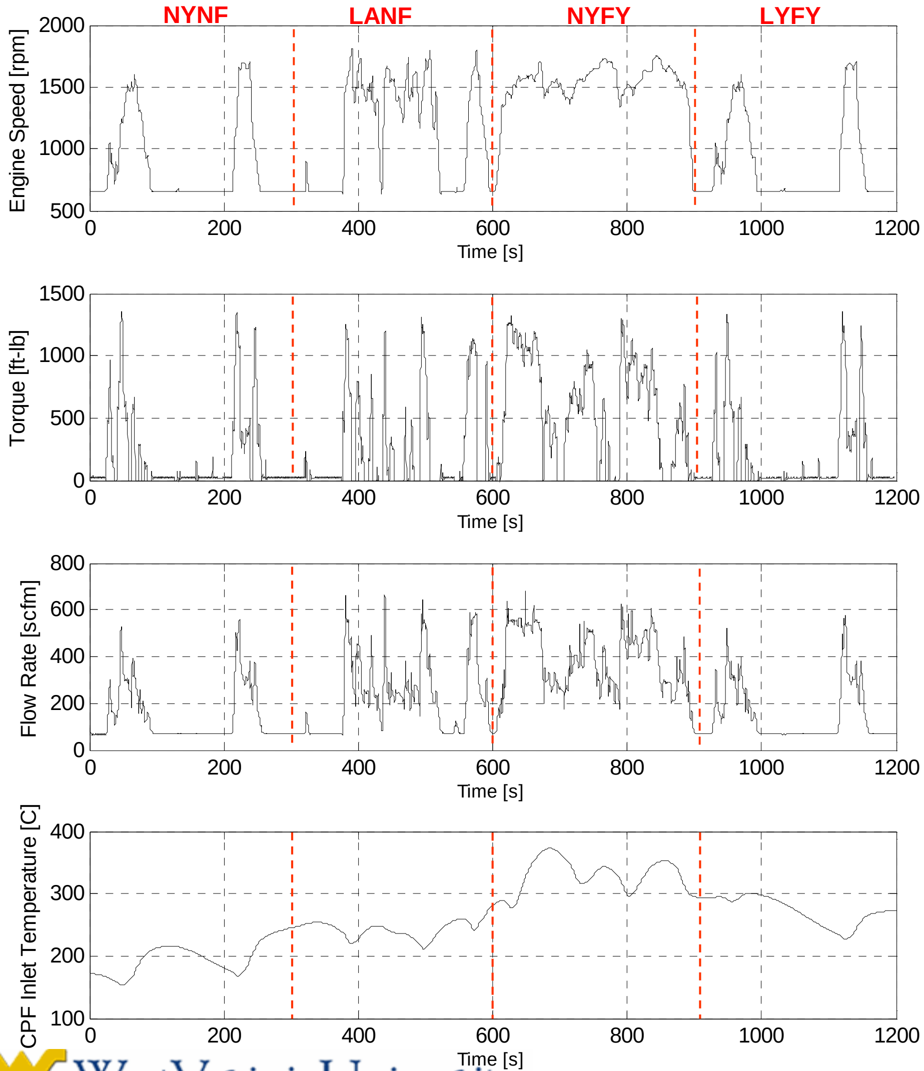
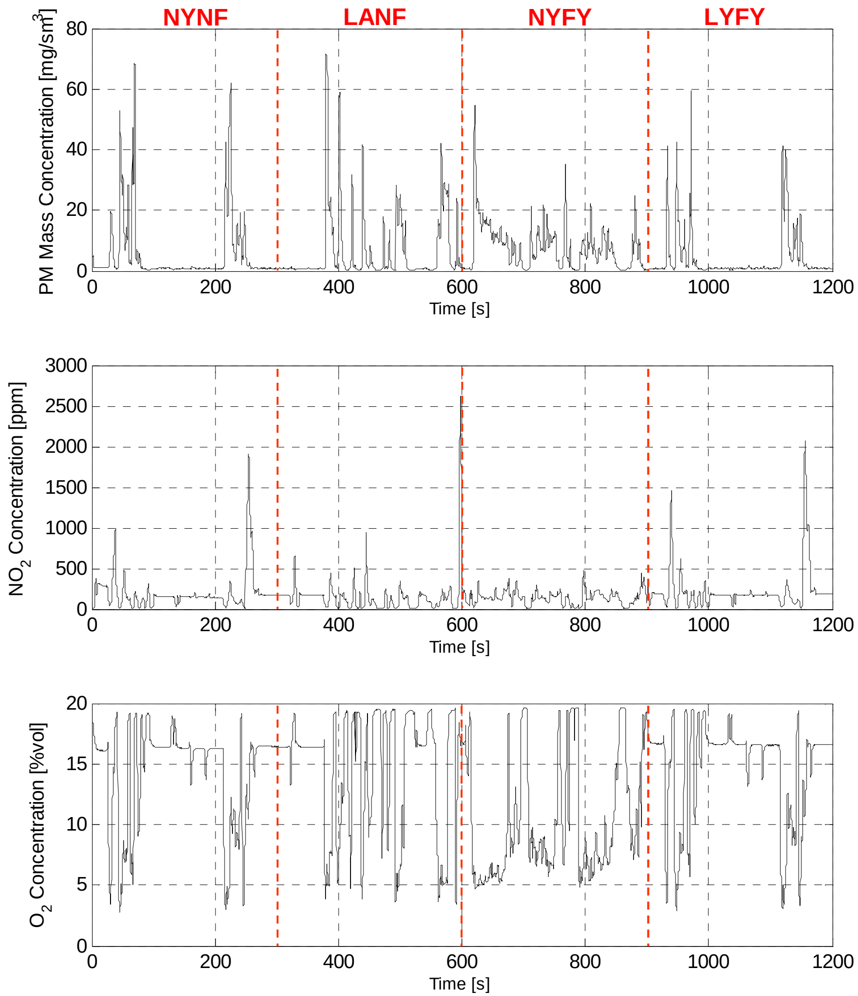
Model Validation

Transient cycle loading





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Model Validation

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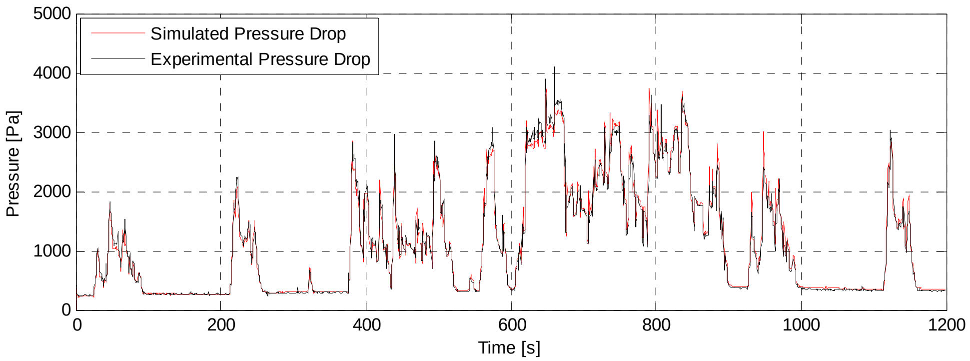

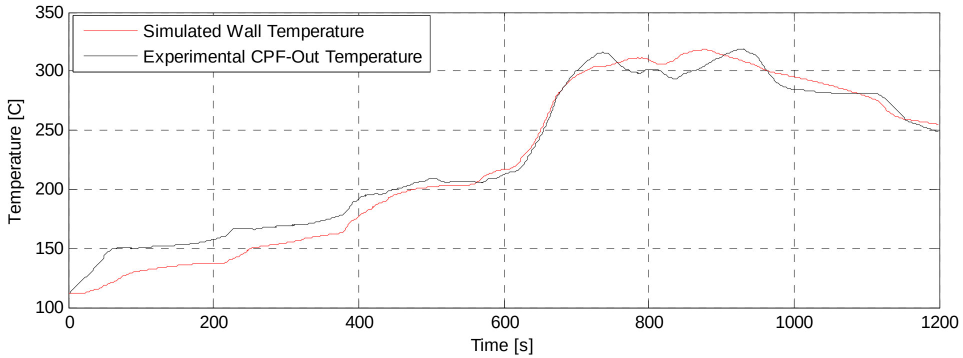

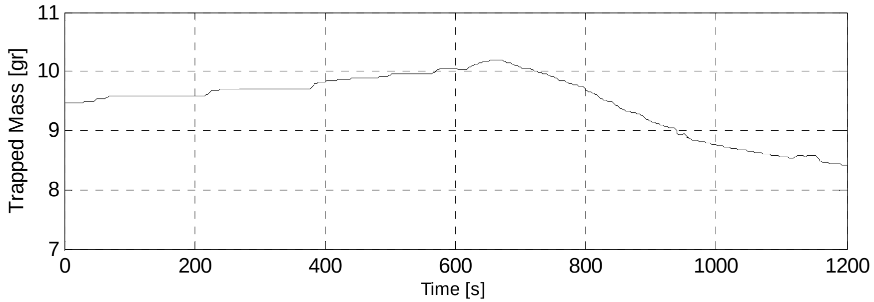

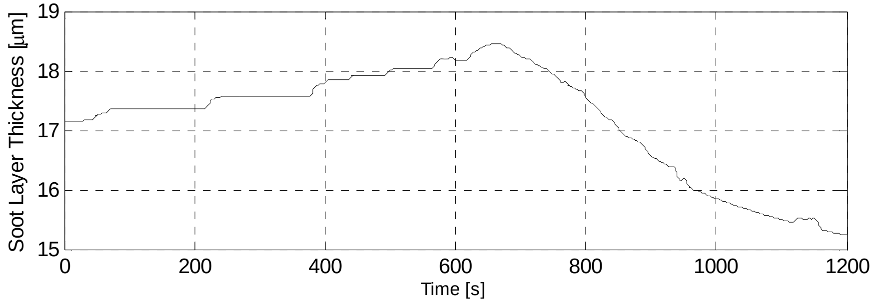

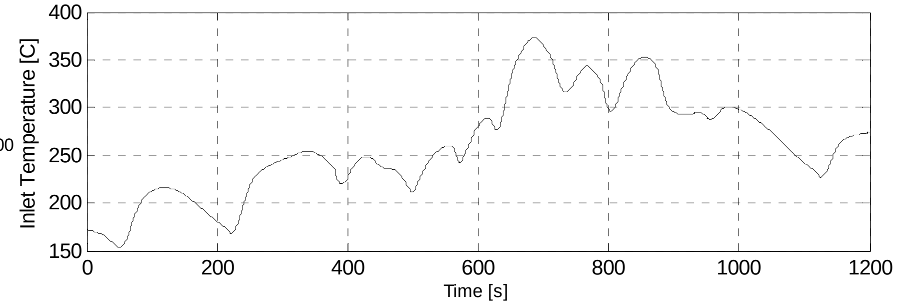

Conclusions

- Model capable of replicating DPF conditions after loading/regeneration cycles
- Satisfactory comparison with engine experimental data
- Different sets of constants (tuning parameters) are not required for transient and steady state loading cycles
- Real-time PM signal during transient cycle

Future developments

- Integration with real time PM sensor for OBD applications
- 2D Model
- Definition of regeneration strategies

Soot Modeling for Advanced Control of Diesel Engine Aftertreatment

THANK YOU FOR THE ATTENTION

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1. Cozzolini, A., Mulone, V., Abeyratne, P., Littera,D., Gautam, M., "Advanced Modeling of Diesel Particulate Filters to Predict Soot Accumulation and Pressure Drop", SAE Technical Paper, 2011-24- 0187, Internal Combustion Engine Congress Capri, Italy, September 2011. (Accepted for Publication).
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