Modeling Active Regeneration of a Diesel Particulate Filter – An Update on Research at Michigan Tech

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CLEERS Workshop 12

University of Michigan - Dearborn

April 29th, 2009

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Outline

- Introduction
- Research Plan
- MTU CPF Model v3.5 – Sub-models Used
- Experimental Data & Simulation Results
- Summary

Introduction

- Research involving active regeneration of diesel particulate filters has been ongoing at MTU since 2004
- MTU has published literature work in SAE on the topic since 2006
- 1-D CPF Model (version 3.0) developed at MTU as part of PhD Research (SAE: 2009-01-1283)
- MTU 1-D CPF Model version 3.5 is discussed today
- Numerical modeling effort at MTU supported by ***John Deere***
- Experimental data collection effort supported by ***Cummins***
- Conversion of 1-D CPF Model (version 3.5) from FORTRAN to MATLAB/Simulink® supported by ***Navistar***

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CPF Model version 3.0* to 3.5

Improvements in:

- Convergence criteria
- Adaptive time-step (relaxation) algorithm
- Code memory requirements (size of memory used has been reduced)
- Outputs & output file formats

*** SAE:2009-01-1283**

Planned Research Work in 2009

- Development of mass transport and coupling chemical reactions with transport (to be included in version 4.0)
- Development of a multi-channel model (CPF HT version 1.0) for including heat transfer and flow distribution, and thereby radial variations during active regeneration
- Analysis of John Deere experimental data using CPF model version 4.0 and CPF HT version 1.0

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PM Oxidation Model

- PM oxidation occurs in PM cake and substrate wall
- Reaction rate constants follow modified Arrhenius form:

$$k_i = A_i T^{x_i} e^{\left(-\frac{E_{a,i}}{RT}\right)}$$

- Model can also include PM oxidation in inlet and outlet channels
- Oxidation occurs via 2 mechanisms:
  1. Thermal ($C + O_2 \rightarrow CO + CO_2$), and
  2. NO_2-assisted ($C + NO_2 \rightarrow CO + CO_2 + NO$)
- 2-layer feature maintained for PM oxidation – catalytic oxidation feature turned off for calibration of experimental data

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PM Filtration Model

- PM filtration occurs in PM cake and substrate wall
- PM cake efficiency at clean state is zero; Substrate wall is only filtration element
- PM cake efficiency is calculated as a function of local PM cake thickness:

$$\eta_{cake} = A_{\eta}\left(1 - e^{\left[-w_{cake}\frac{\eta_c}{d_{c,cake}}\right]}\right)$$

- Substrate wall efficiency is a function of amount of PM collected and wall properties

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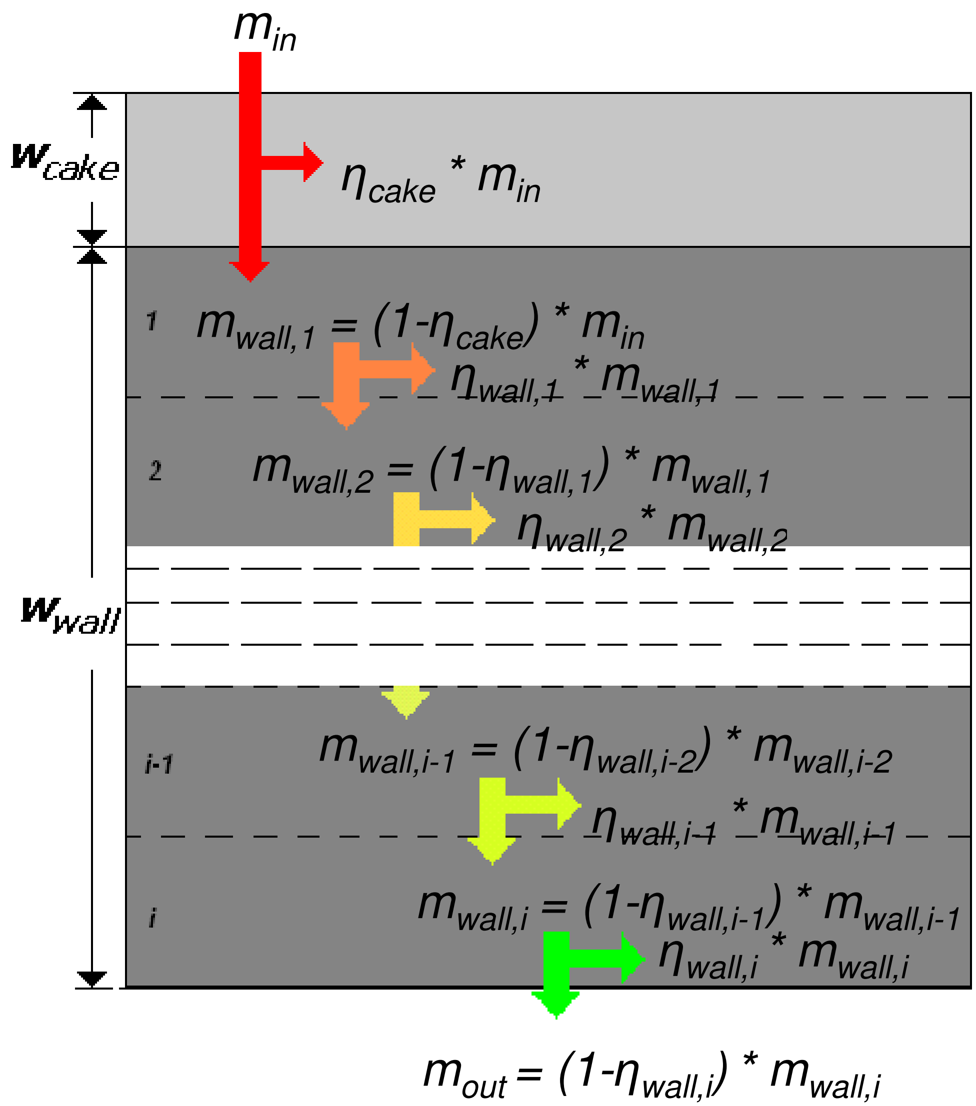
PM Filtration – 2 Sequential Filters Approach



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PM Cake Permeability Model

- PM Cake permeability is a function of molecular mean free path and in turn, local gaseous temperature (theory adapted from Versaeval et al, SAE, 2000)

$$k_p(t) = k_p(loading)\frac{\lambda(t)}{\lambda(loading)}$$

where:

$$\lambda = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2(MW_{exh})}}$$

- Packing density of PM in cake assumed constant (~*130 kg/m³*) according to Pe number (Konstandopoulos et al, SAE, 2002)

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Critical Elements of Modeling Pressure Drop During Active Regeneration

- Permeability of PM Cake
- Oxidation of PM Cake
- Oxidation of PM in Substrate Wall
- Evolution of Filtration Efficiency

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Experimental Data
(SAE:2009-01-1474, SAE:2009-01-1274)

Cummins ISM 2002 10.8 liter engine

- *Turbo-charged*
- *After-cooled*

Fuel – ULSF

- *API Gravity =* 36.8 (at 15.5°C)
- Cetane Index = 46.2
- Sulfur content = 8-10 ppm

Cummins 2007 RPF (DOC+CPF) System

- *10.5x4/400 DOC (Pt alloy) (Vol.= 5.7 liters) and*
- *10.5x12/200 CPF (Pt) (Vol. = 17.0 liters)*

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Load-Case Description: Run 17
(4.1 g/l, 600°C, 70% PM oxid.)

Loading:-

- Start engine at 2100 rpm engine load and 20% engine load (exh. temp = 282°C);
- 5 hrs and 15 mins at 2100 rpm and 20% load to obtain 4.1 g/l target PM loading;
- Ramp down engine; shut off; weigh CPF substrate

Active regeneration:-

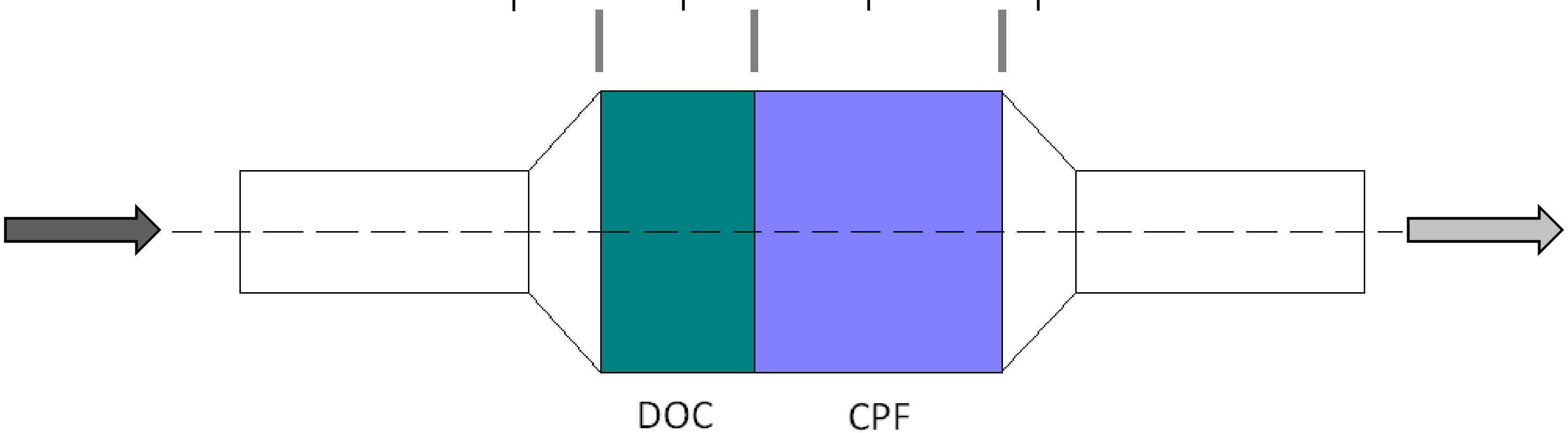
- Re-start engine at 2100 rpm and 20% load (~1 minute);
- Switch to 2100 rpm and 40% load (~3 minutes) (exh. temp = 341°C);
- Start doser fuel injection to achieve a target CPF inlet temperature of 600°C ;
- ~7 minutes of active regeneration to achieve 70% (of the PM at end-of-loading) PM oxidation (UPDOC HC conc. = 19678 ppmC, UPCPF HC Conc. = 4223 ppmC);
- Ramp down engine (~4 minutes); shut off; re-weigh CPF substrate

Post-loading:-

- Re-start engine at 2100 rpm and 20% load;
- 1hr at 2100 rpm and 20% load;
- Engine shut-off; re-weigh CPF substrate

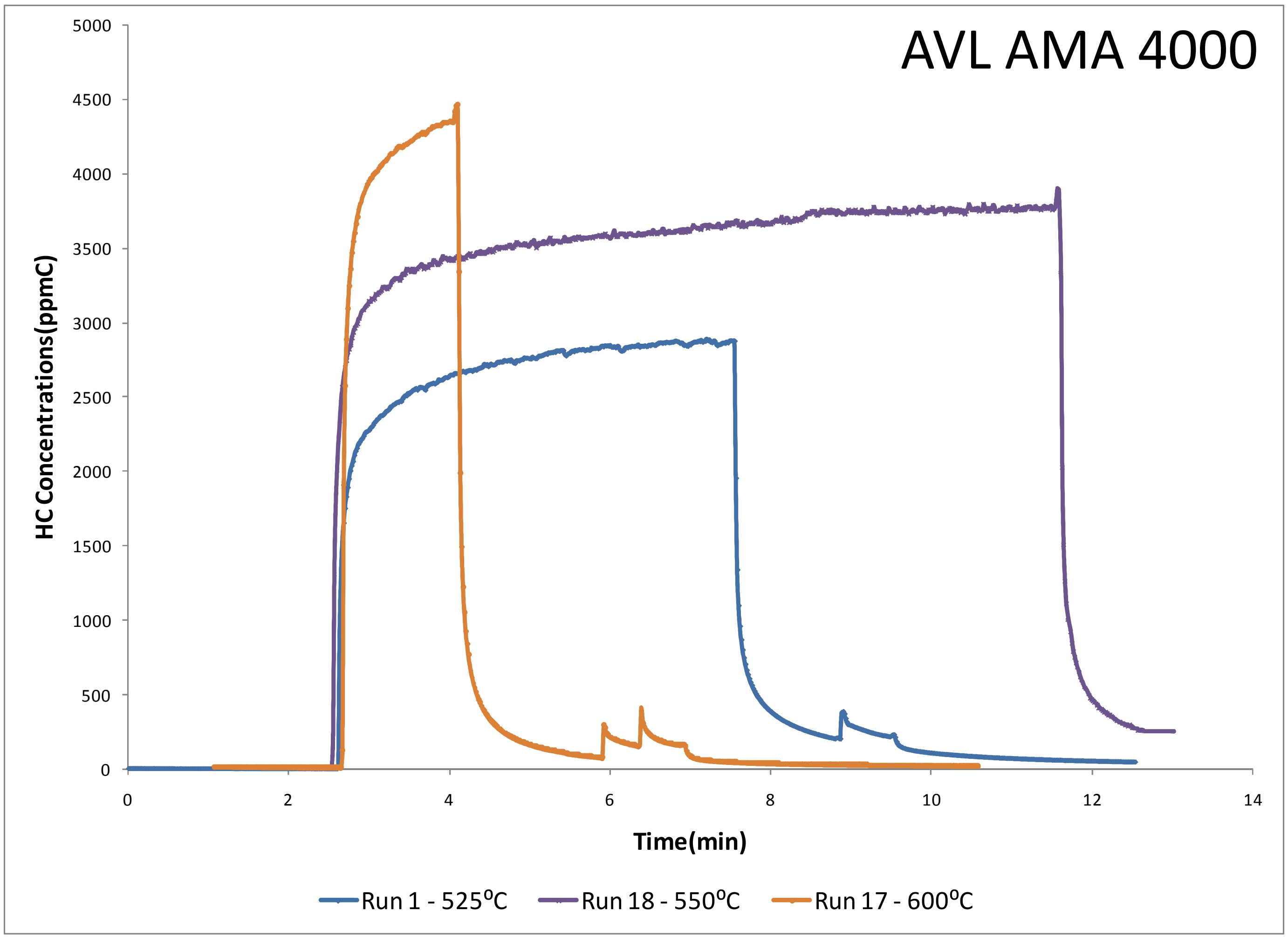
RUN17 Active Regeneration Overview

Temp.	321	590	668	°C
Flow rate		320		g/s
HC's	19678	4223	12	ppmC
CO	90	101	0	ppm
NO	196	186	213	ppm
NO_2	29	43	22	ppm



SAE: 2009-01-1283

Typical HC Concentration Measurements Made During Active Regeneration



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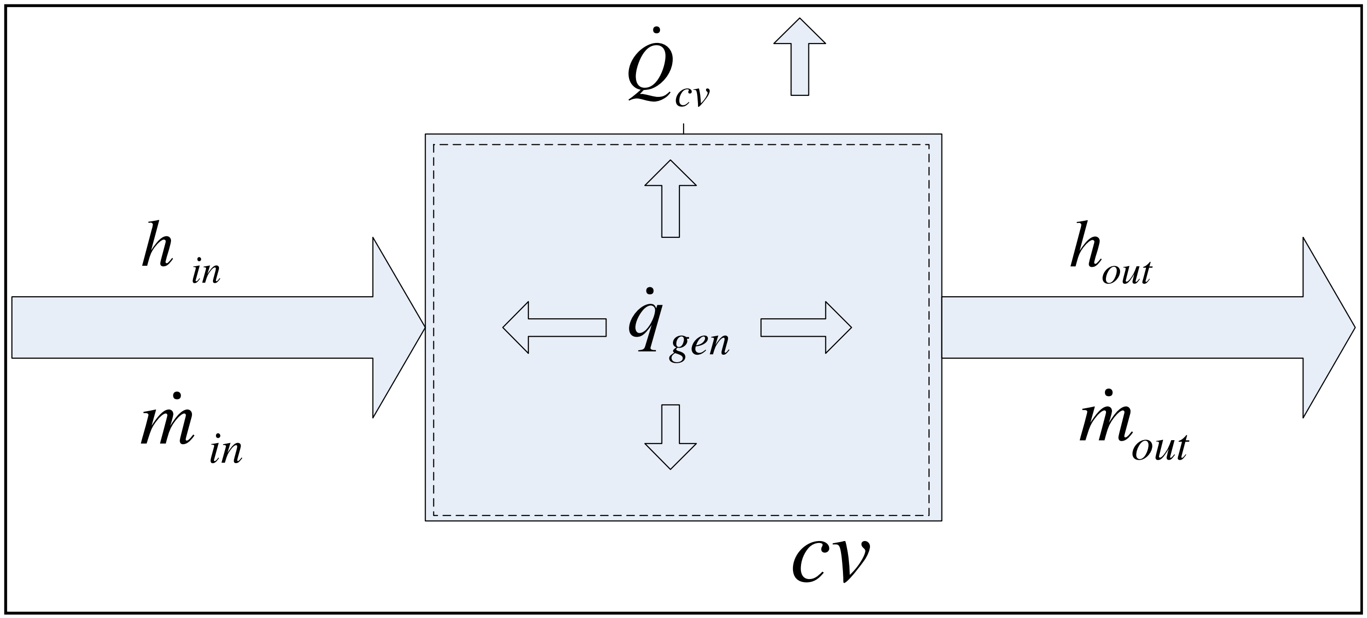
Corrections for HC Concentration Data

- Uses Steady-state Energy Balance
- Heat transfer to the ambient is assumed to be through free convection
- Temperature Data is Used to Better Estimate Concentrations of Hydrocarbons (as $C_{12}H_{24}$), First at Inlet to CPF and Then at Inlet to DOC

Energy Balance Approach

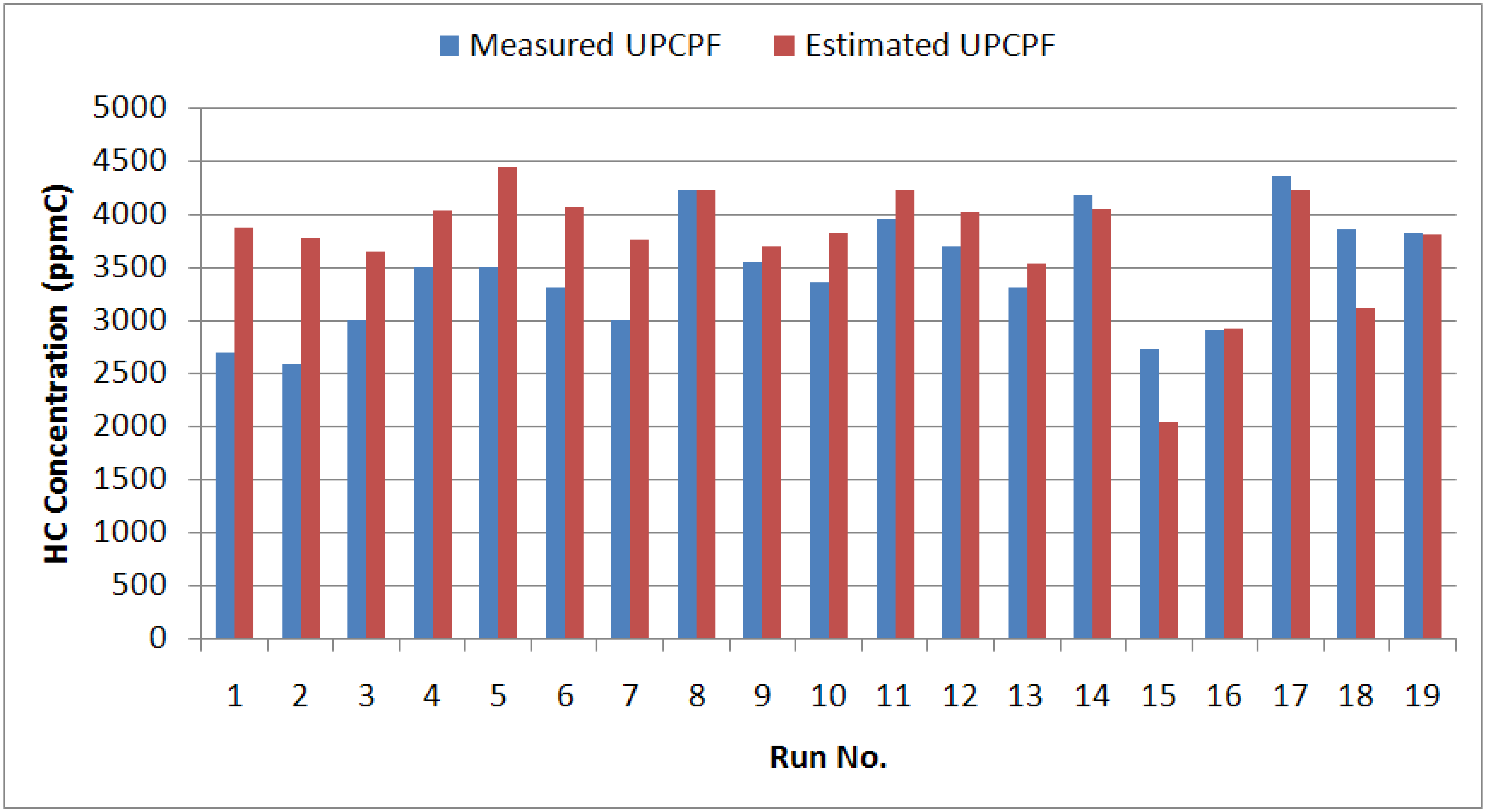
$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{q}_{gen} + \sum \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) - \sum \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$



$$[HC]_{(CPF,in)} = f\left([HC]_{(CPF,out)}, \Delta\dot{H}(CO), \Delta\dot{H}(NO), \Delta\dot{H}(C-O_2), \Delta\dot{H}(C-NO_2), T_{(CPF,in)}, T_{(CPF,out)}, \dot{Q}_{amb}, \dot{m}_{exh}\right)$$

$$[HC]_{(DOC,in)} = f^{*}\left([HC]_{(CPF,in)}, \Delta\dot{H}(CO), \Delta\dot{H}(NO), T_{(DOC,in)}, T_{(DOC,out)}, \dot{Q}_{amb}, \dot{m}_{exh}\right)$$

Estimated HC Concentrations During Active Regeneration – All Runs



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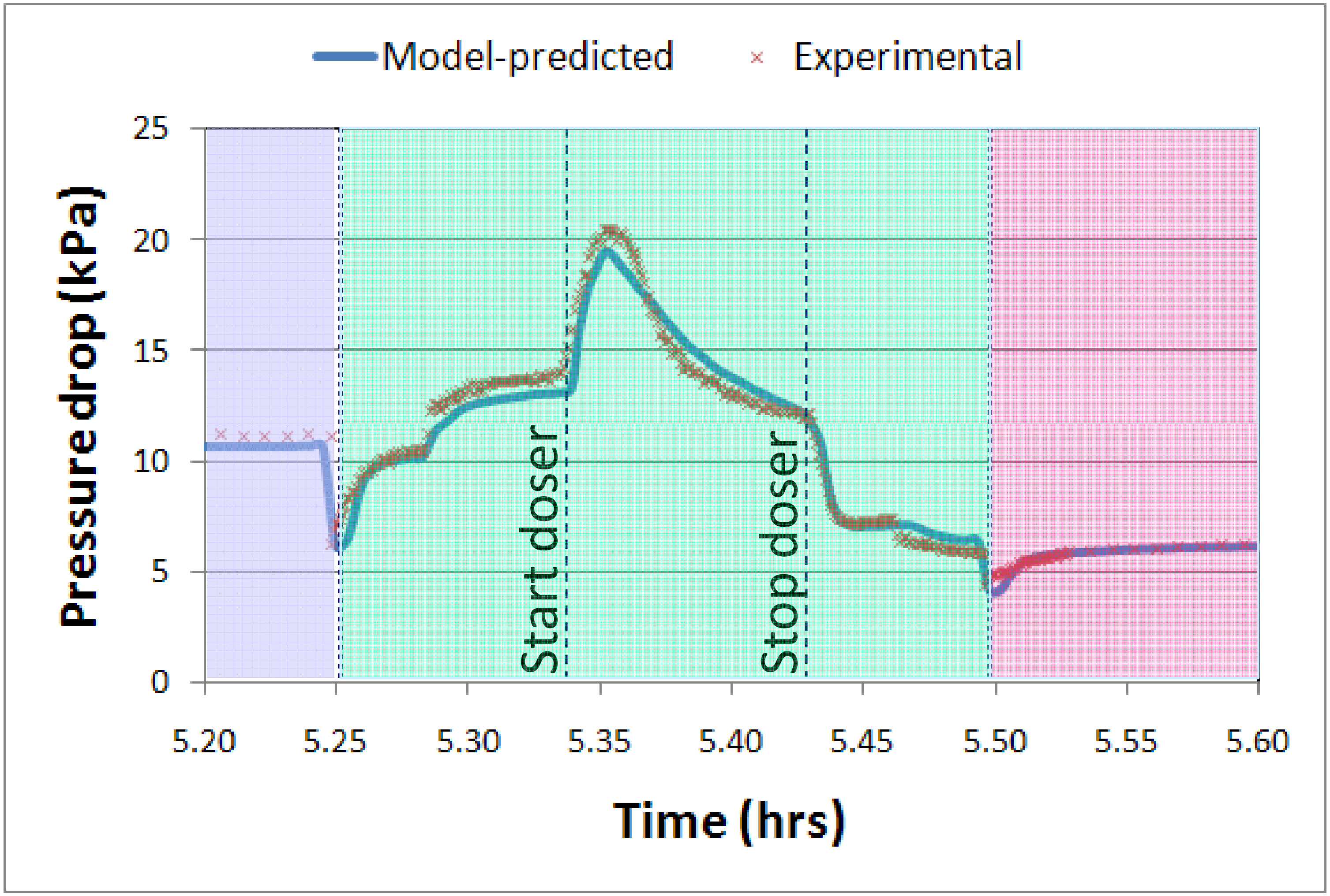
CPF Pressure Drop during Active Regeneration

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



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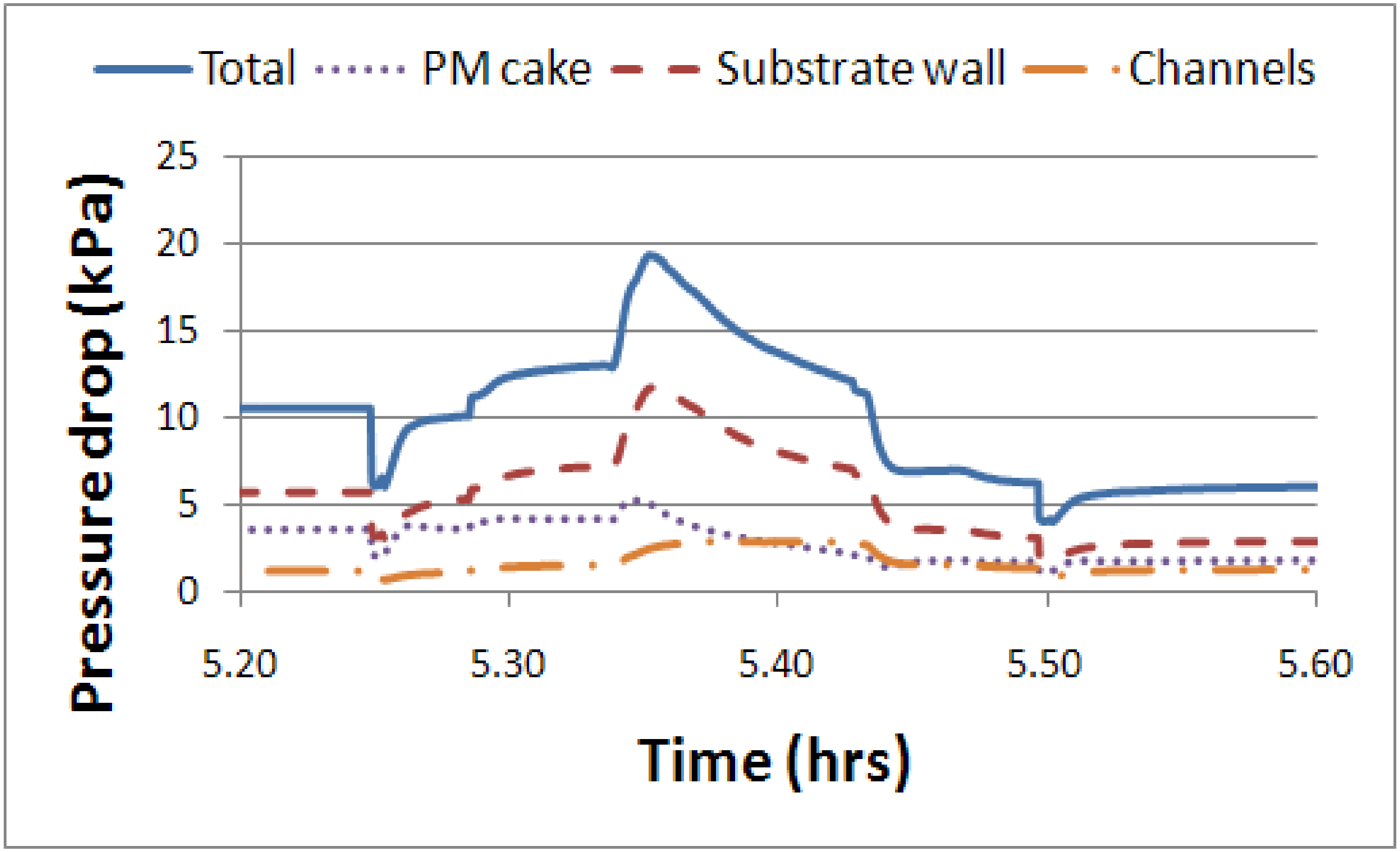
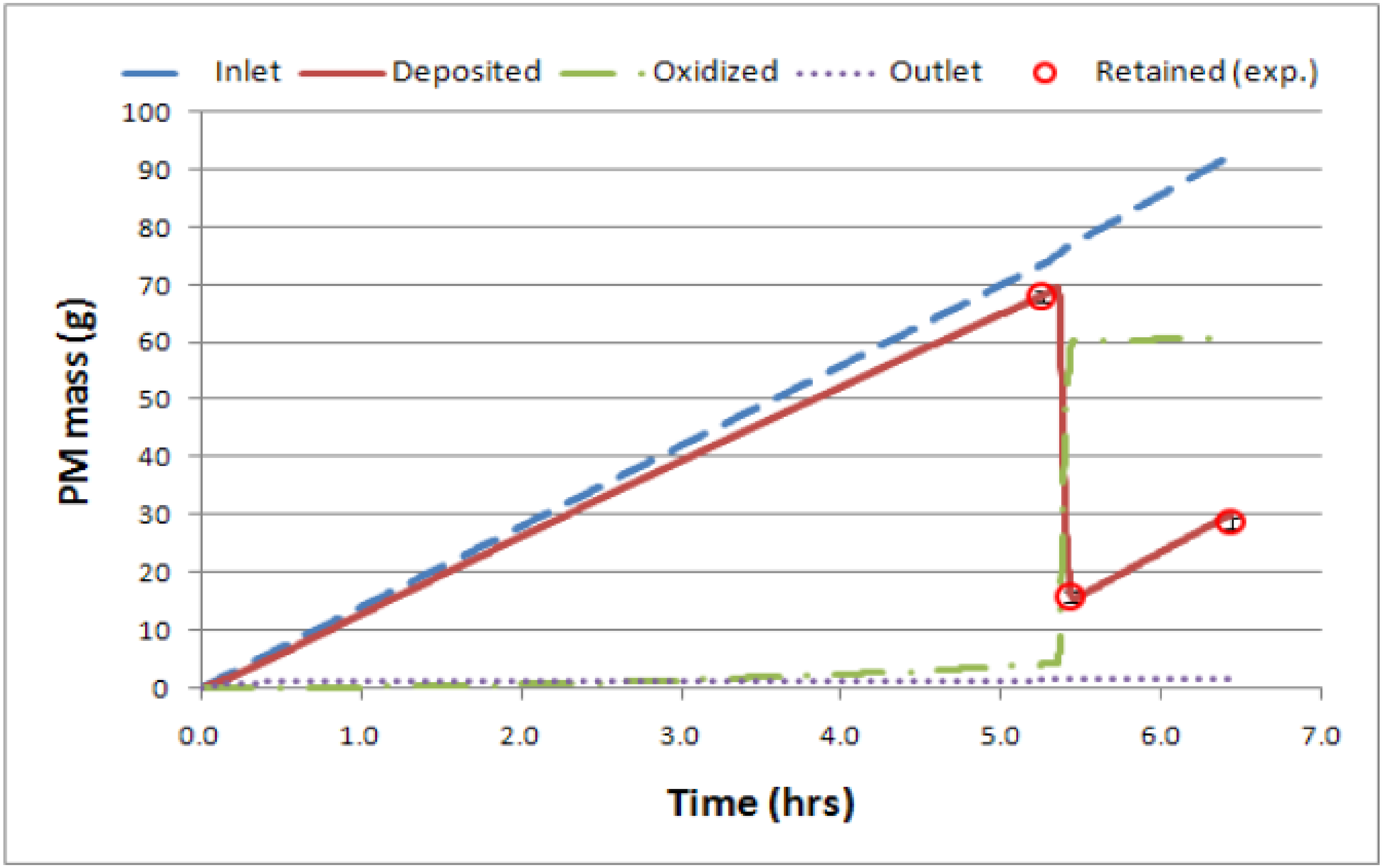
Components of Overall Pressure Drop during Active Regeneration

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



PM Mass Balance

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



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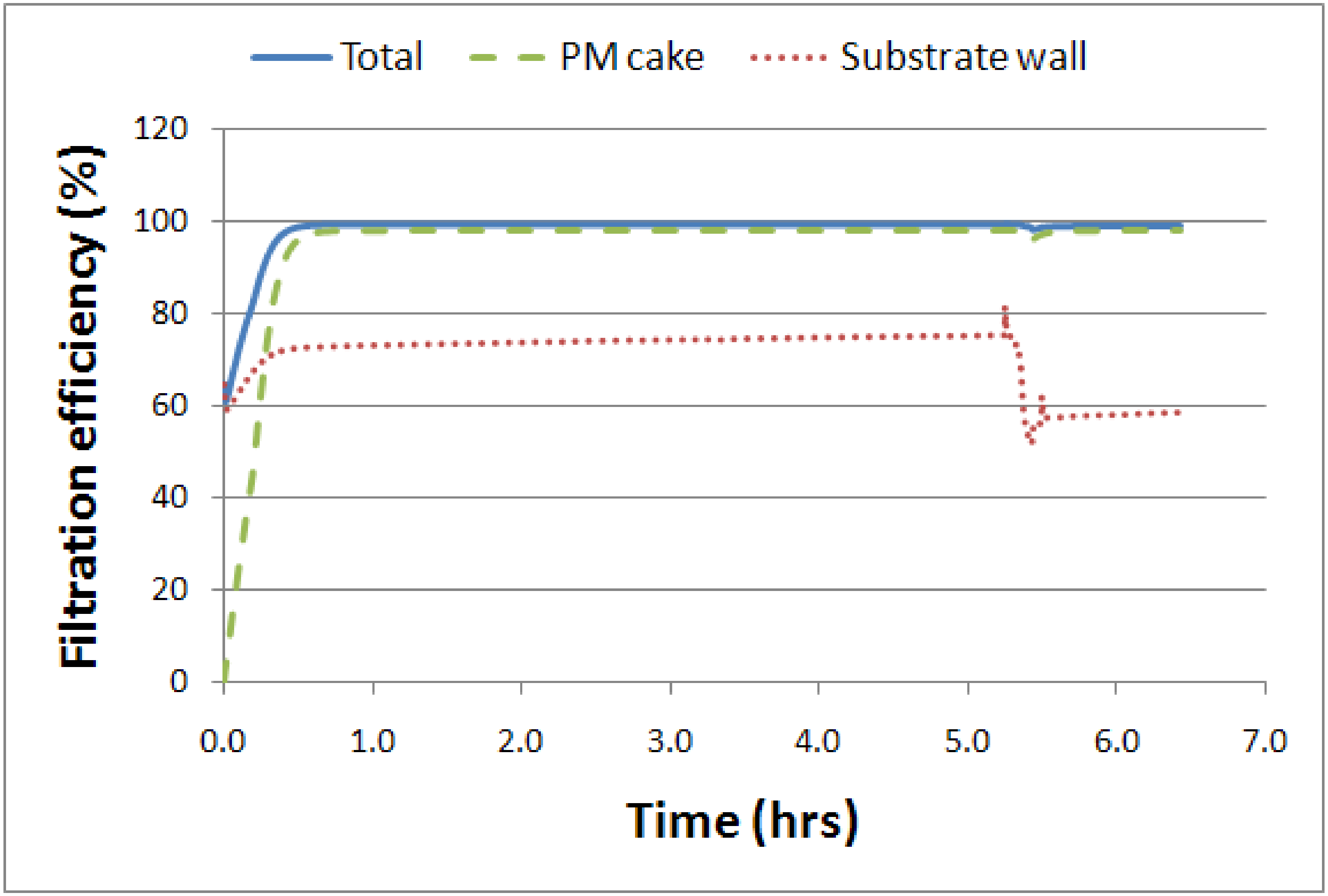
PM Filtration Efficiency

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



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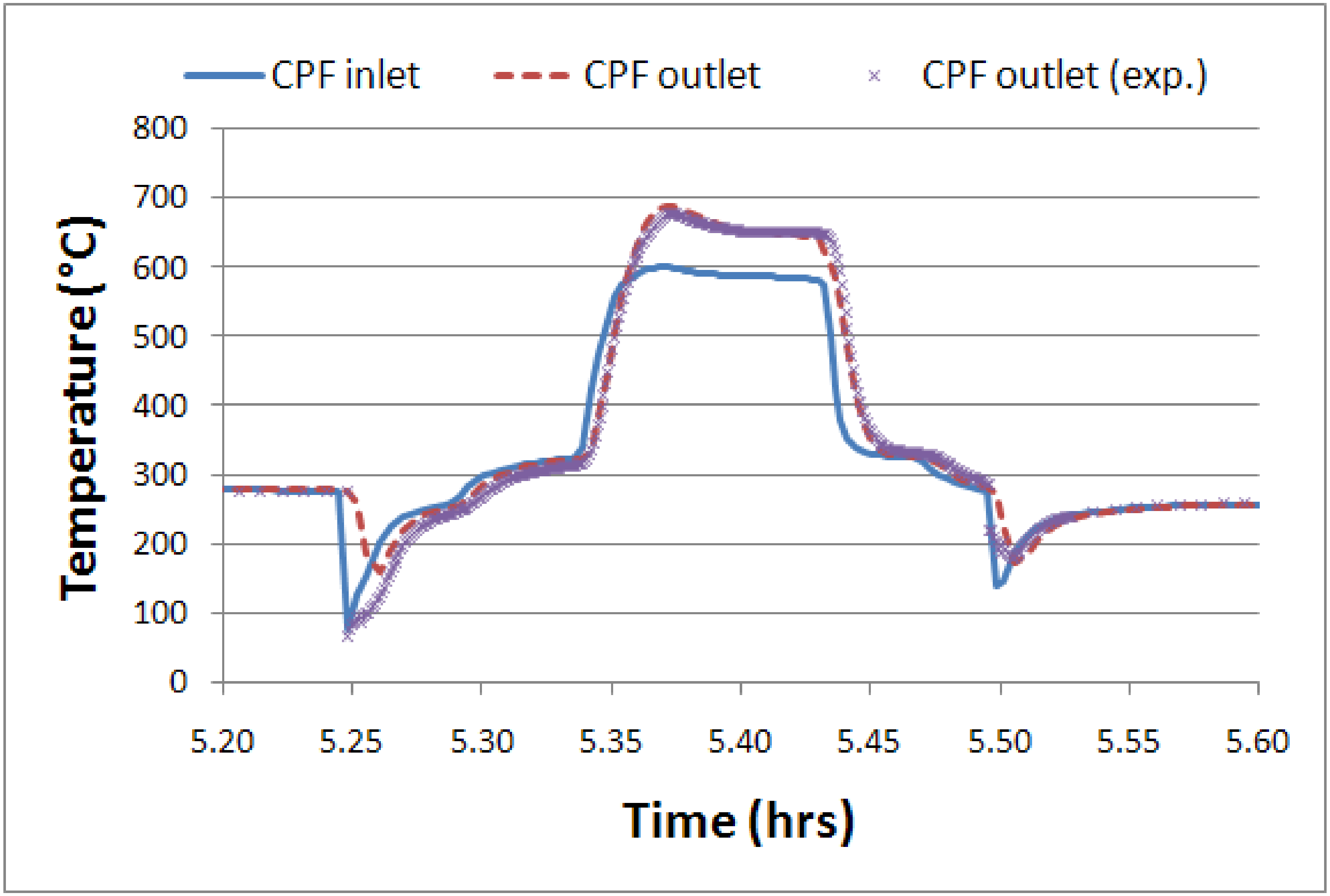
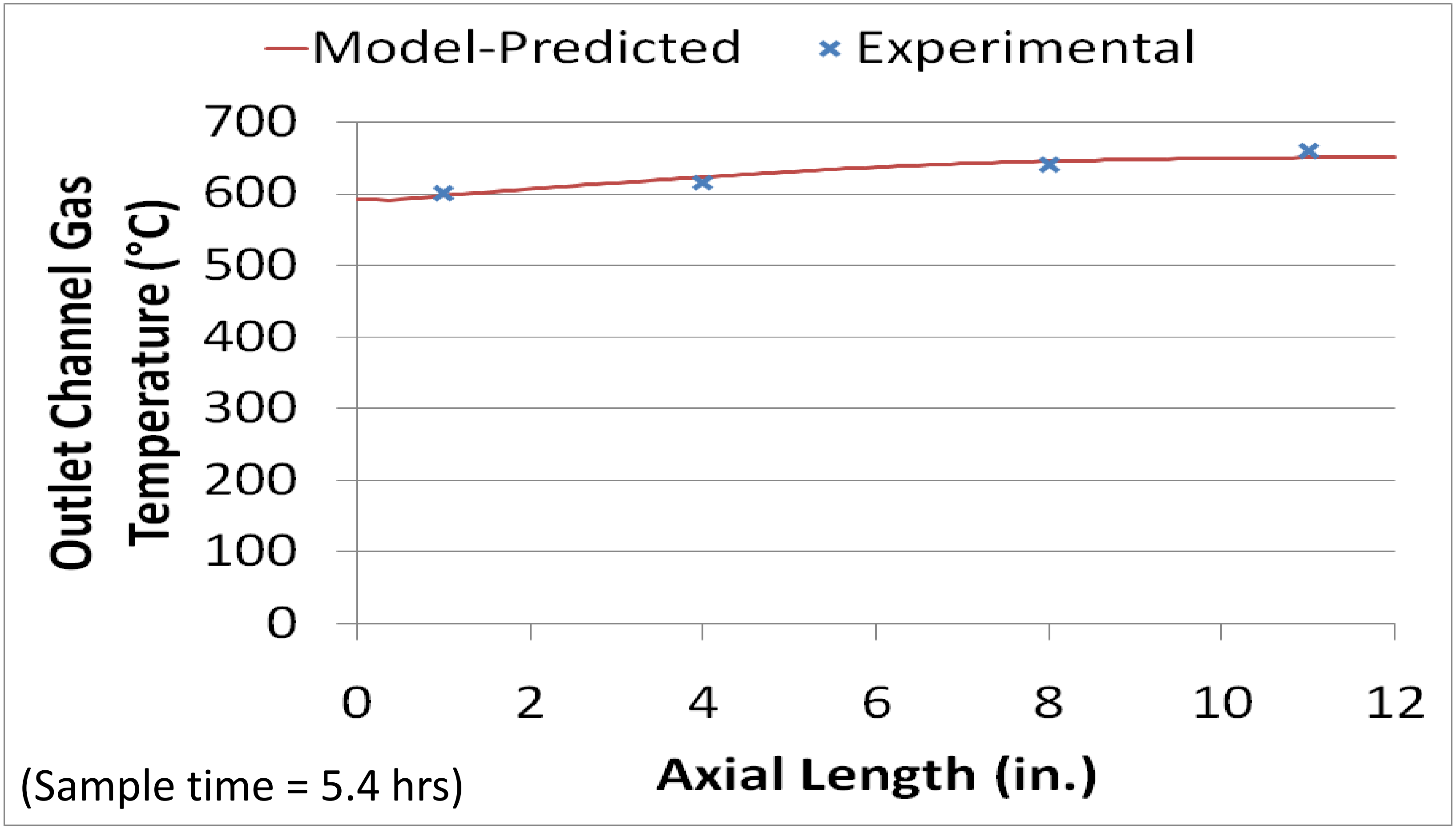
CPF Outlet Gas Temperature Comparison

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



Axial Gas Temperature Profile during Active Regeneration

Run 17 (4.1 g/l, 600°C, 70% PM oxid.)



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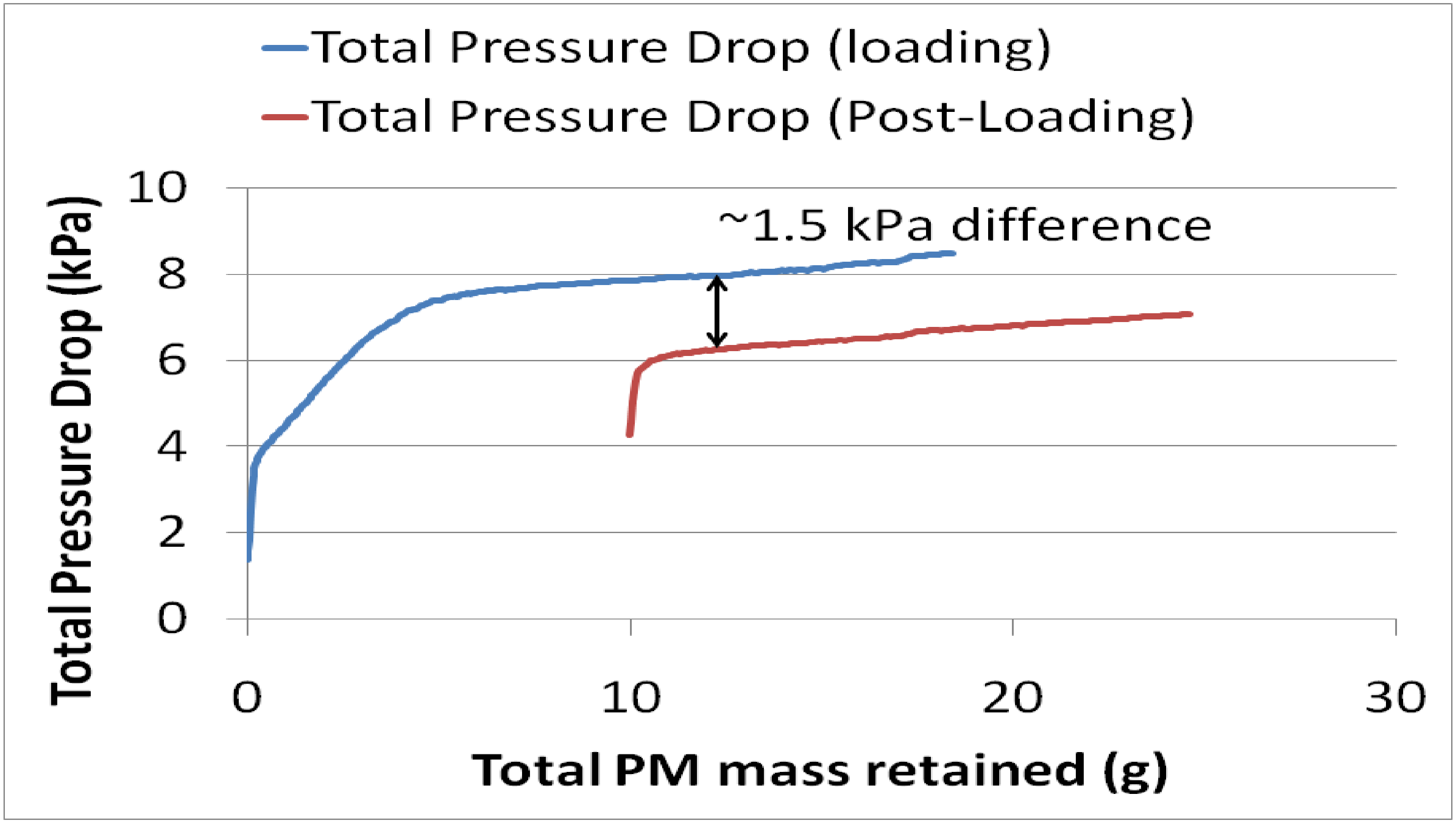
CPF Pressure Drop During Loading and Post-Loading

Run 1 (1.1 g/l, 525°C, 60% PM oxid.)



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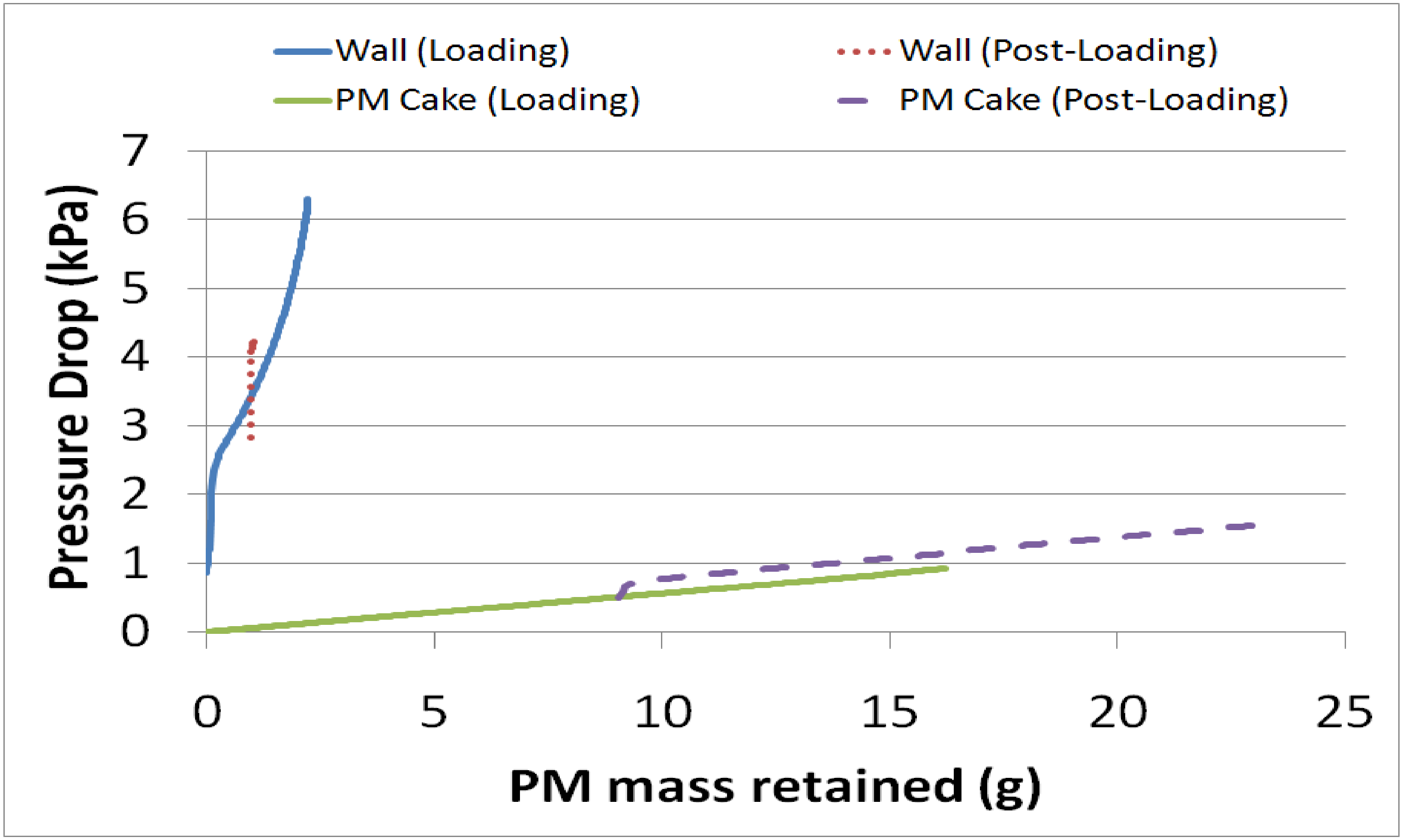
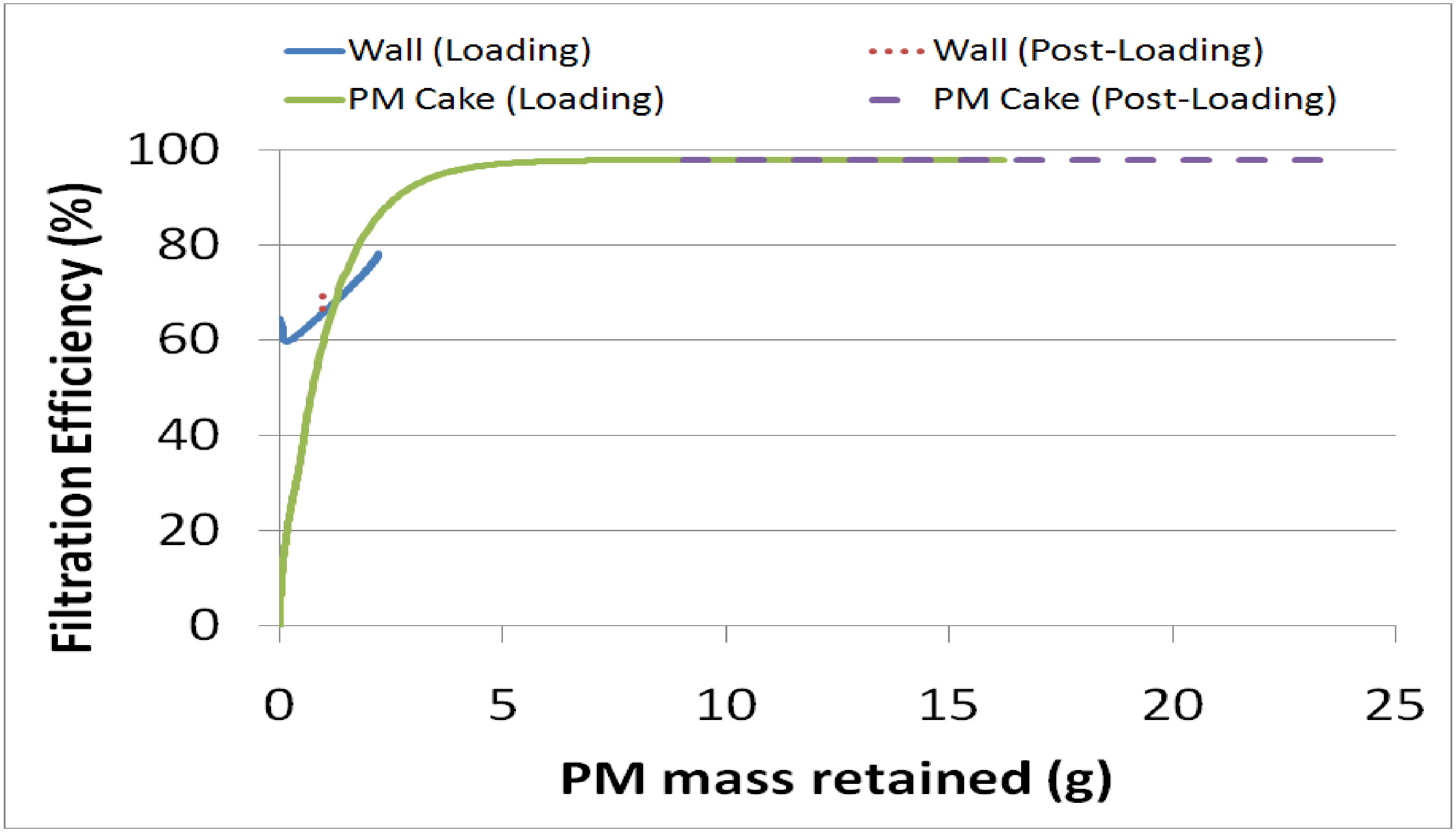
CPF Pressure Drop Components During Loading and Post-Loading

Run 1 (1.1 g/l,525, 60% PM oxid.)



Filtration Efficiencies During Loading and Post-Loading

Run 1 (1.1 g/l,525, 60% PM oxid.)



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Summary

- *1-D Active Regeneration CPF Model version 3.5 developed; testing & calibration to experimental data ongoing at MTU*
- *Future work in CPF modeling – including gas-solid mass transport to substrate from channels*
- *Improvements in PM cake filtration efficiency calculations*
- *Multi-channel approach to simulate radial variations in behavior of CPF during active regeneration is ongoing*
- *Integrated active regeneration DOC-CPF model validated using John Deere experimental data is final product of research work*

QUESTIONS?