Use of the MTU 1-D 2-layer CPF Model to Understand Filtration and Oxidation Characteristics of a DOC-CPF system

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Overview of this Presentation

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- ***INTRODUCTION***
- ***EXPERIMENTAL SETUP AND TEST MATRIX***
- ***CPF MODEL & CALIBRATION***
- ***CPF MODEL ANALYSIS & RESULTS***
- ***CONCLUSIONS & SUMMARY***

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Research Objectives

1. Collect experimental data for characterizing CPF-only and CCRT® (DOC-CPF) performance,

2. Develop MTU 1-D 2-layer CPF model based on experimental data obtained to improve filtration characteristics from previous model,

3. Calibrate model input parameters to match experimental data values of:
    - *CPF clean pressure drop,*
    - *CPF pressure drop vs. time,*
    - *PM mass deposited at end of loading,*
    - *DN-CPF PSD data from SMPS, and*
    - *DN-CPF NO_2 concentrations.*

4. Use calibrated CPF model to analyze effect of load and configuration on filtration and oxidation of CPF.

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Engine:

Engine Specifications

2004 John Deere 6068H (DEV)

- **4-stroke, 6.8 liter 6 cyl. In-line turbo-charged, after-cooled**
- **187 kW max. power at 2200 rpm**
- **995 Nm max. torque at 1650 rpm**
- **Electronically controlled variable injection timing**
- **High-Pressure common-rail fuel system**
- **Cooled Low-Pressure loop EGR (22% to 18% Dry vol. basis)**

Fuel:

Dynamometer Specifications

- **ULSF (Sulfur Content= *11.6* ppm)**
- **Specific Gravity at 15°C = *0.8417***
- **API Gravity at 15°C = *36.6***
- **Cetane Number = *48.2***

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Fuel Specifications

DOC:

- ***Cordierite***, ***10.5*** **in. Dia. X** ***6*** **in. Length (*8.5* liters)**
- **Cell Density = *400* cpsi (cell repeat distance = *50* mil)**
- **Wall Thickness = *6* mil (original) + *2* mil (wash-coat) = *8* mil**
- **Bulk Density = *440* kg/m^3**

CPF:

DOC Specifications CPF Specifications

- ***Cordierite***, ***10.5*** **in. Dia. X** ***12*** **in. Length (*17.0* liters)**
- **Cell Density = *200* cpsi (cell repeat distance = *71* mil)**
- **Wall Thickness = *12* mil, Channel Width = *59* mil**
- **Mean Pore Size = *11* µm**
- **Clean porosity = *50%***
- **Bulk Density = *390* kg/m^3**

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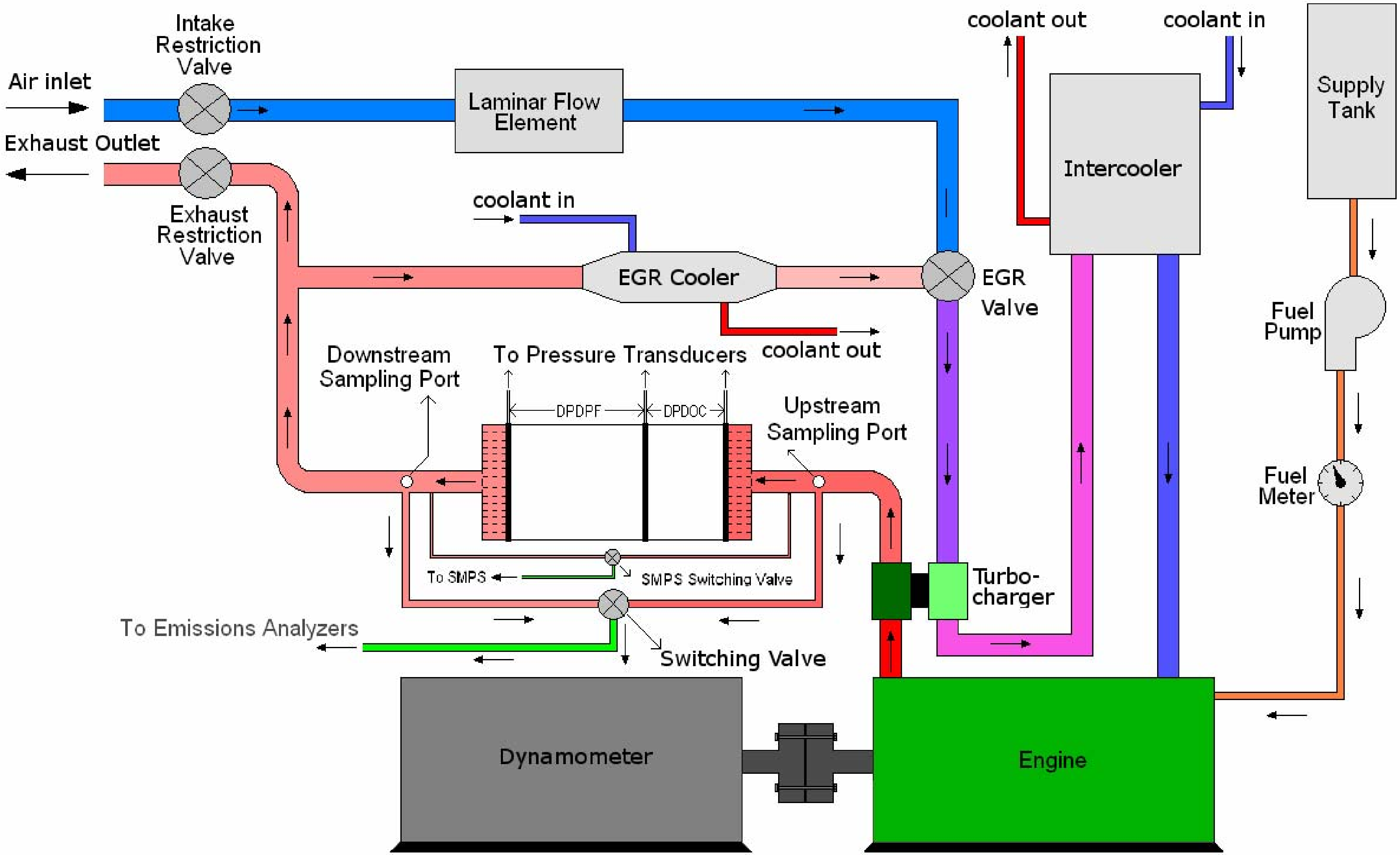
General Setup for Experiments



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Test Matrix for Experiments – CPF-only and CCRT® (cont'd)

16 experiments conducted:

- ➢ 4 load-cases (25%, 50%, 75% and 100%)
- x 2 configurations (CPF-only and CCRT®)
- x 2 speeds (2200 and 1650 rpm)

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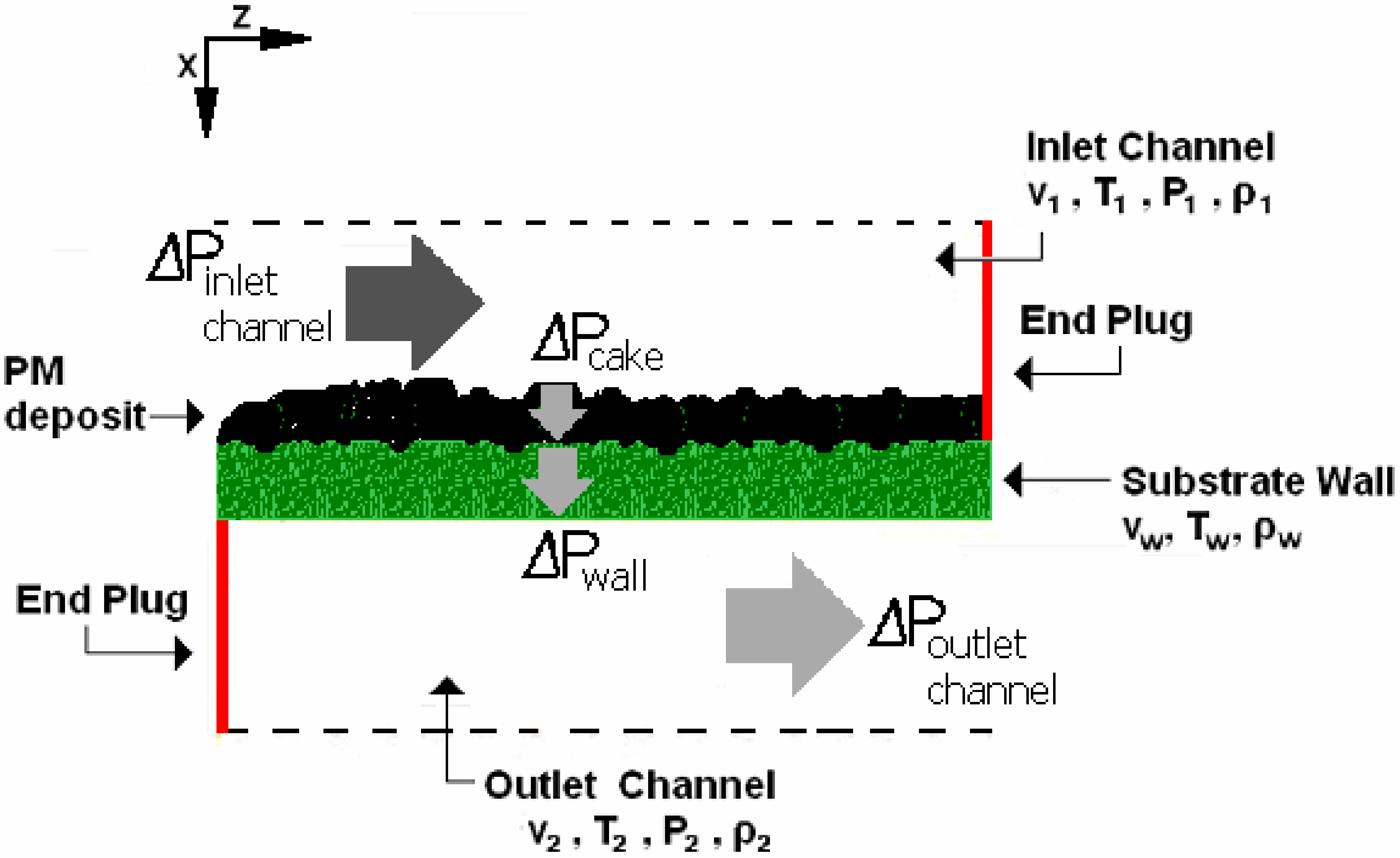
MTU 1D 2-Layer CPF Model - Features

1. 1D Steady/Quasi-steady Model (FILTRATION, OXIDATION)
2. Uses "2 filters in series" approach for filtration – (Cake + Wall)
3. Fortran environment (MTU DPF model also in MATLAB/simulink)
4. Solves for :
   - ***CPF Pressure Drop as function of loading time, and its components,***
   - ***Mass Distribution in the CPF,***
   - ***Filtration Efficiency (Cake, Wall and Overall) and DS-Particle Size Distributions***
   - ***Particulate Cake Layer Thickness,***
   - ***Inlet, Outlet and Wall Temperatures,***
   - ***Gas velocities, and***
   - ***Distribution of Mass Oxidized by location and mechanism.***
5. All Inputs in 4 ASCII text files (1 for CPF input variables and exhaust gas composition (CO_2, H_2O, O_2 and N_2 mole fractions), 1 each for transient inlet temperature, standard inlet particulate concentration and standard volumetric flow rate).

MTU 1D 2-Layer CPF Model – Single Channel Schematic



Improvements to MTU 1D 2-layer CPF model

- Oxidation inside the pores of the filter wall by thermal and by NO_2 / Temperature assisted oxidation*,
- Particulate cake filtration model — model the porous cake parametrically and couple the filtration and oxidation models of the filter wall and particulate cake layer*, and
- Oxidation of particulate by NO_2 produced in the catalyst washcoat of the CPF*.

* **Described in Hasan et al. -** ***SAE:2006-01-0467***

Particulate Cake Filtration Modeling

- Earlier version of cake filtration model did not couple properly with the overall filtration model.
- Once the cake forms, it is more natural and useful to describe the filtration by means of particulate cake parameters which are separate from the wall.
- This is the equivalent of separately simulating filtration by cake followed by wall filtration (shown in next slide).
- Cake filtration efficiency is modeled by a parametric equation (§).
- Partition coefficient* (Φ) is used to initiate solution, since there is no cake layer at the beginning of loading.

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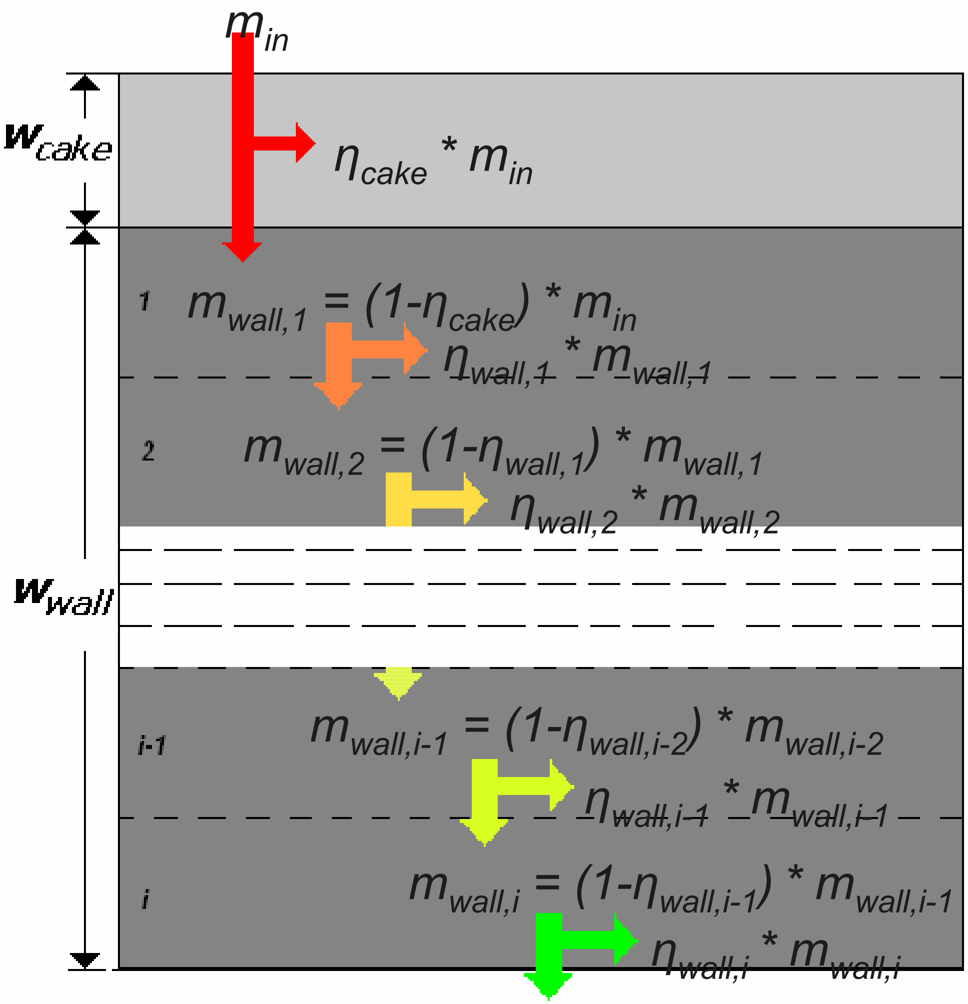
* **Reference – Konstandopoulos et al. - *SAE:2000-01-1016***

Particulate Cake Filtration Modeling – “2 filters in series” Approach



m_{in}

w_{cake}

$\eta_{cake} * m_{in}$

w_{wall}

1 $m_{wall,1} = (1-\eta_{cake}) * m_{in}$

$\eta_{wall,1} * m_{wall,1}$

2 $m_{wall,2} = (1-\eta_{wall,1}) * m_{wall,1}$

$\eta_{wall,2} * m_{wall,2}$

i-1 $m_{wall,i-1} = (1-\eta_{wall,i-2}) * m_{wall,i-2}$

$\eta_{wall,i-1} * m_{wall,i-1}$

i $m_{wall,i} = (1-\eta_{wall,i-1}) * m_{wall,i-1}$

$\eta_{wall,i} * m_{wall,i}$

$m_{out} = (1-\eta_{wall,i}) * m_{wall,i}$

Particulate Cake Filtration Modeling – Efficiency Equation

- Parametric equation (§) is used to model cake filtration efficiency* (η_{cake}).

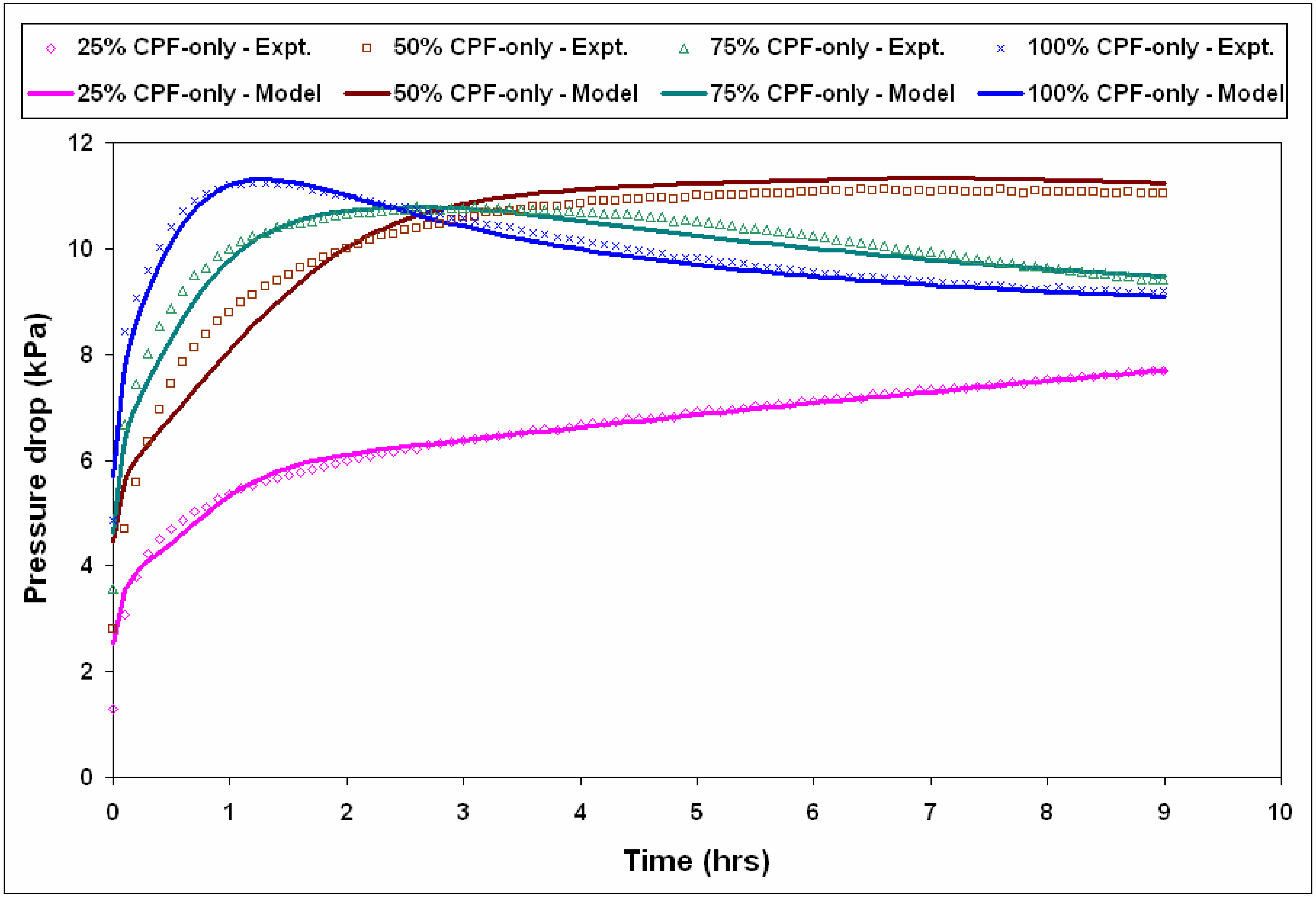
$$\boxed{\eta_{cake} = A_\eta \left(1 - e^{-w_{cake} \cdot \frac{\eta_c}{d_{c,cake}}}\right)} \dashrightarrow (\S)$$

A_η	is used to predict cake efficiencies less than 100% at all PM loads (this is an empirical addition to theory)
$\eta_c/d_{c,cake}$	is the ratio of individual cake collector efficiency to cake collector diameter
w_{cake}	is the local PM cake layer thickness

* **Wark, Warner and Davis - *Air pollution : Its Origin and Control* (Addison-Wesley, 2002)**

Model Calibration Results – 2200 rpm data

CPF Model Calibration Results for CPF-only Configuration - Model vs. Experimental Pressure Drop Profiles



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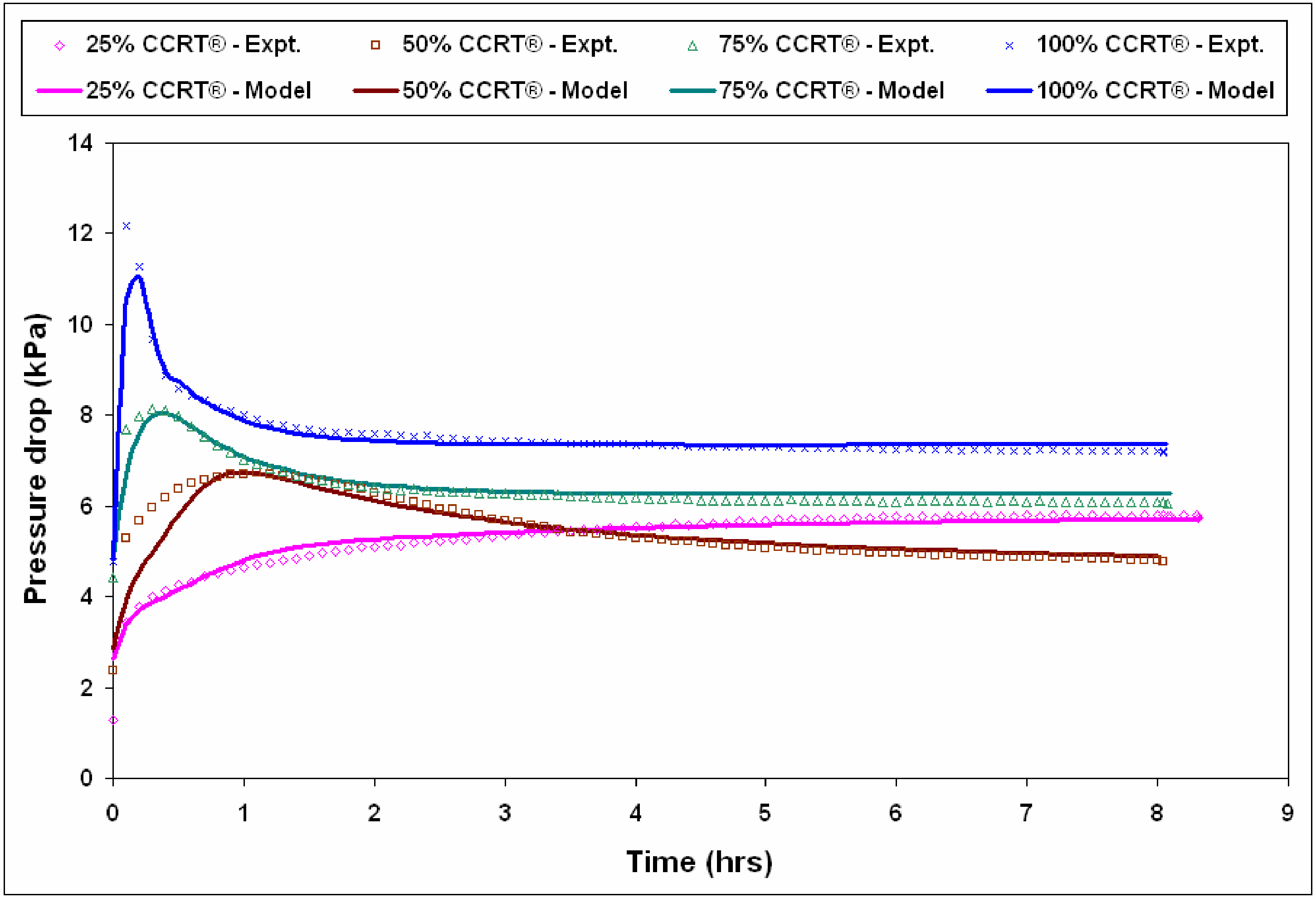
CPF Model Calibration Results for CCRT® Configuration - Model vs. Experimental Pressure Drop Profiles



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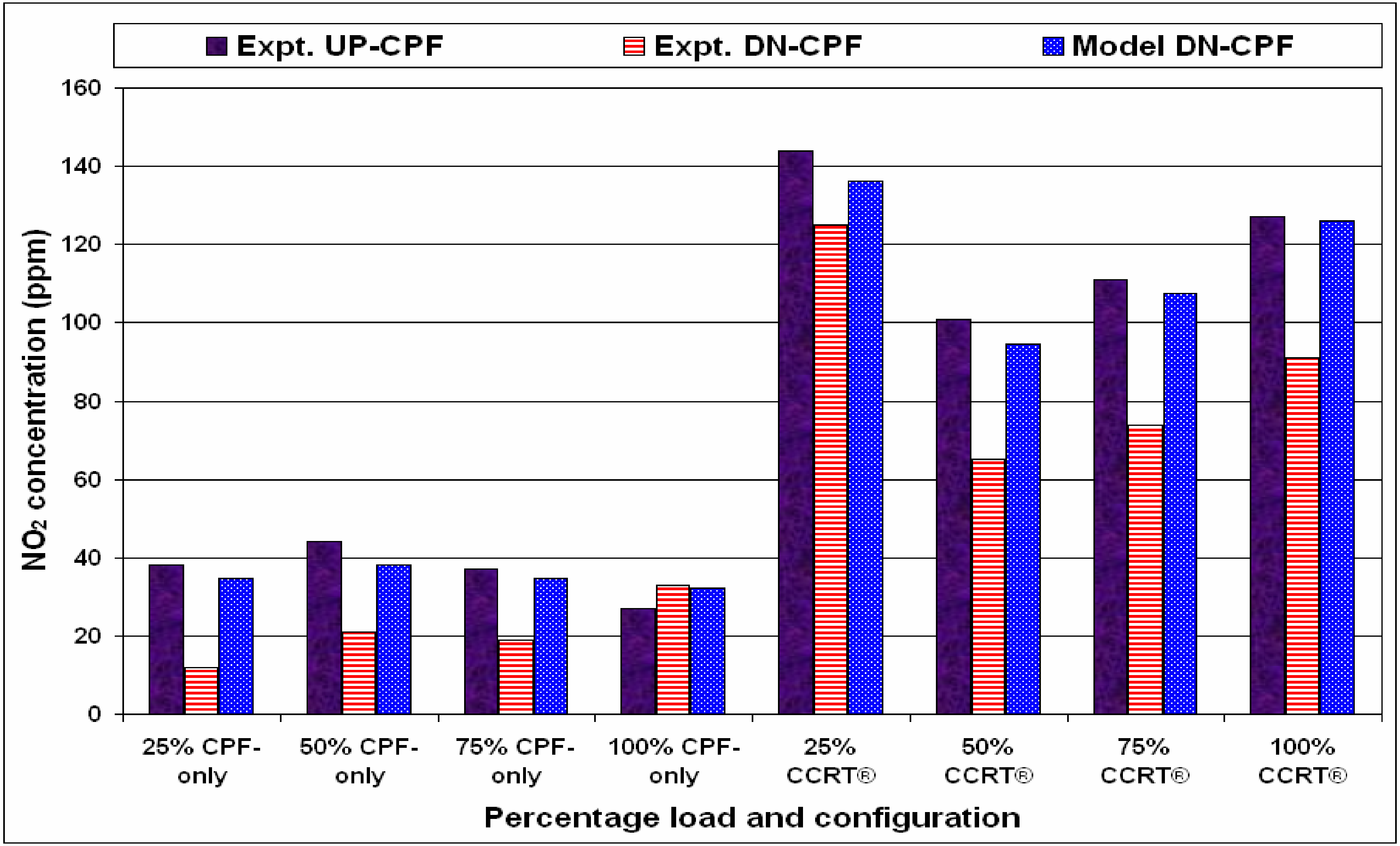
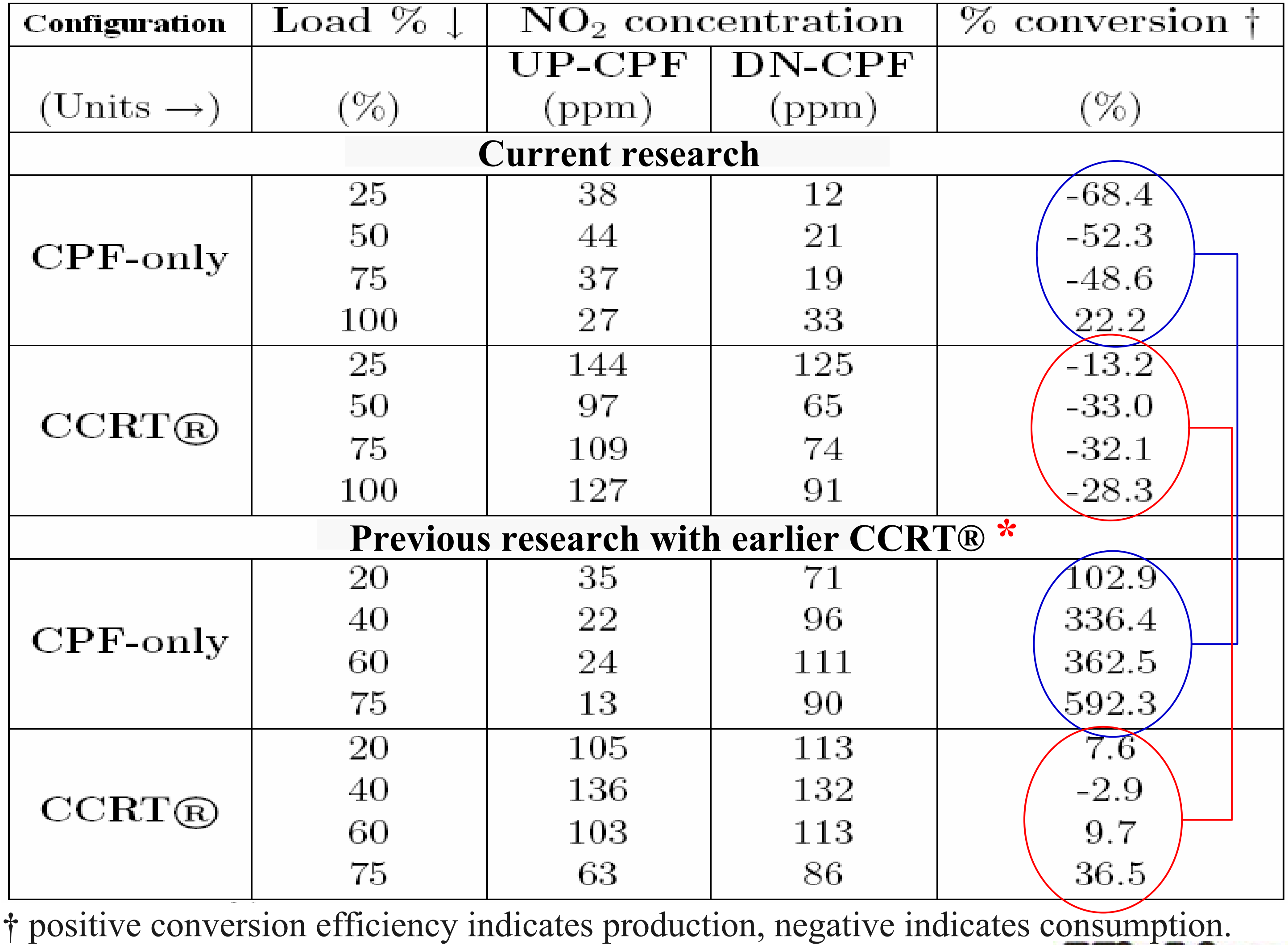
2200 rpm - CPF Model Calibration Results – Model vs. Experimental Mass Oxidized (1 of 2)

Configuration	Load (%)	CPF Inlet Temp. (°C)	Experimental				Model			% difference in PM deposited (%)	% difference in PM oxidized (%)
			Total inlet PM (g)	PM deposited (g)	PM oxidized (g)	% PM oxidized (%)	PM deposited (g)	PM oxidized (g)	% PM oxidized (%)		
CPF-only	25	250	25.3	19.0	6.3	25	22.2	3.14	12	17	-13
	50	343	22.9	16.0	6.9	30	14.1	8.84	39	-12	8
	75	379	19.6	12.0	7.6	39	11.1	8.56	44	-8	5
	100	405	21.4	5.0	16.4	77	7.59	13.8	65	52	-12
CCRT®	25	267	16.0	12.0	4.0	25	8.75	7.28	45	-27	20
	50	364	13.1	6.0	7.0	54	5.94	7.20	55	-1	0
	75	408	15.4	3.0	12.4	81	3.11	12.2	80	4	-1
	100	428	21.1	2.0	19.1	91	2.63	18.4	88	32	-3

CPF Model Calibration Results – Model vs. Experimental CPF Outlet NO_2 Concentrations



*CPF Experimental Results – Comparison of NO_2 Production Effect with Previous Research**

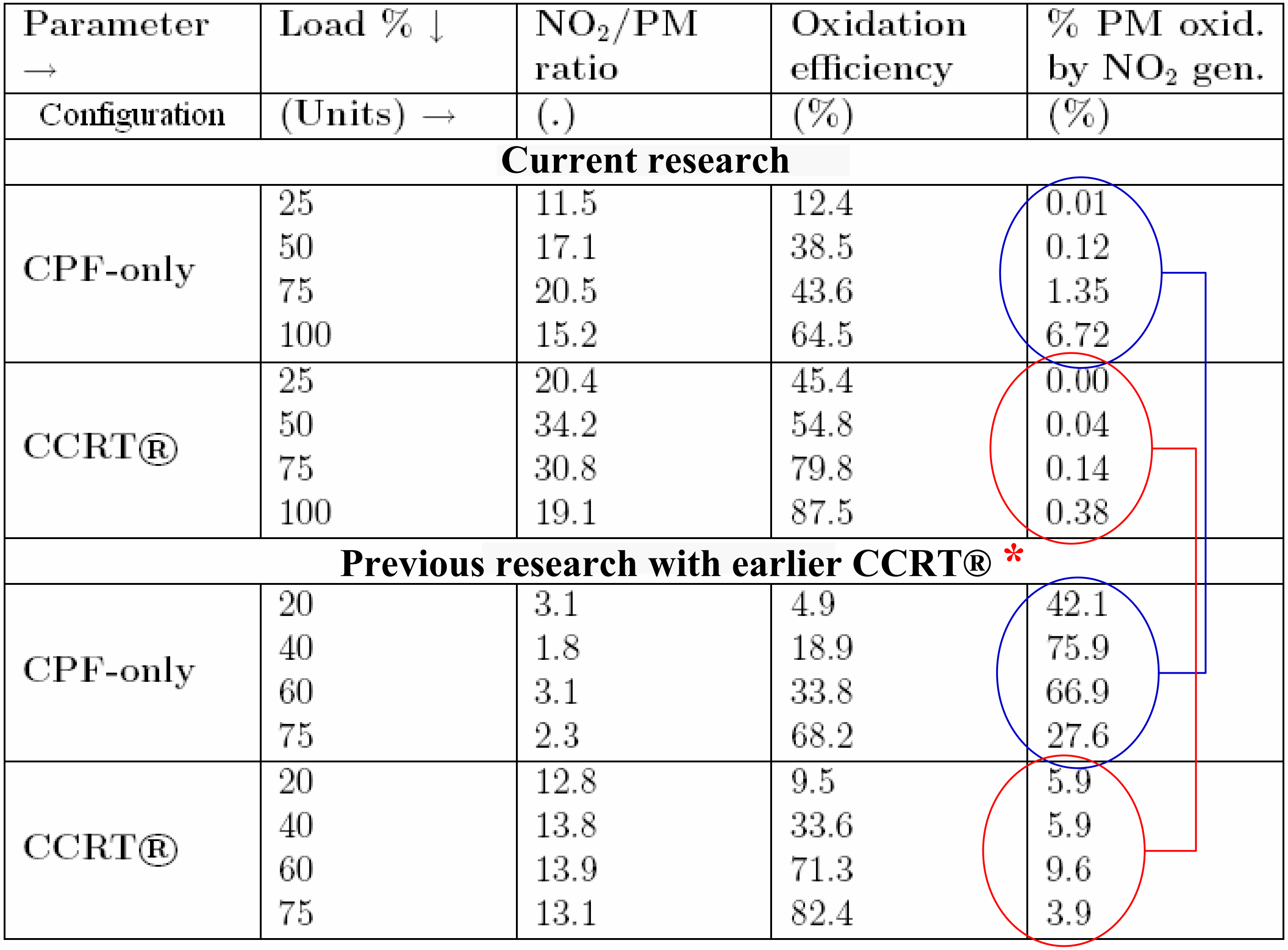


Configuration	Load % ↓	NO_2 concentration		% conversion †
		UP-CPF	DN-CPF	
(Units →)	(%)	(ppm)	(ppm)	(%)
Current research				
CPF-only	25	38	12	-68.4
	50	44	21	-52.3
	75	37	19	-48.6
	100	27	33	22.2
CCRT®	25	144	125	-13.2
	50	97	65	-33.0
	75	109	74	-32.1
	100	127	91	-28.3
Previous research with earlier CCRT® *				
CPF-only	20	35	71	102.9
	40	22	96	336.4
	60	24	111	362.5
	75	13	90	592.3
CCRT®	20	105	113	7.6
	40	136	132	-2.9
	60	103	113	9.7
	75	63	86	36.5

† positive conversion efficiency indicates production, negative indicates consumption.

* Hasan et al. – ***SAE 2006-01-0466 (CUMMINS 2002 ISM Engine)***

CPF Model Results – Comparison of PM Oxidation due to NO_2 Production with Previous Research*



Parameter →	Load % ↓	NO_2/PM ratio	Oxidation efficiency	% PM oxid. by NO_2 gen.
Configuration	(Units) →	(.)	(%)	(%)
Current research				
CPF-only	25 50 75 100	11.5 17.1 20.5 15.2	12.4 38.5 43.6 64.5	0.01 0.12 1.35 6.72
CCRT®	25 50 75 100	20.4 34.2 30.8 19.1	45.4 54.8 79.8 87.5	0.00 0.04 0.14 0.38
Previous research with earlier CCRT® *				
CPF-only	20 40 60 75	3.1 1.8 3.1 2.3	4.9 18.9 33.8 68.2	42.1 75.9 66.9 27.6
CCRT®	20 40 60 75	12.8 13.8 13.9 13.1	9.5 33.6 71.3 82.4	5.9 5.9 9.6 3.9

* Hasan et al. – *SAE 2006-01-0466 (CUMMINS 2002 ISM Engine)*

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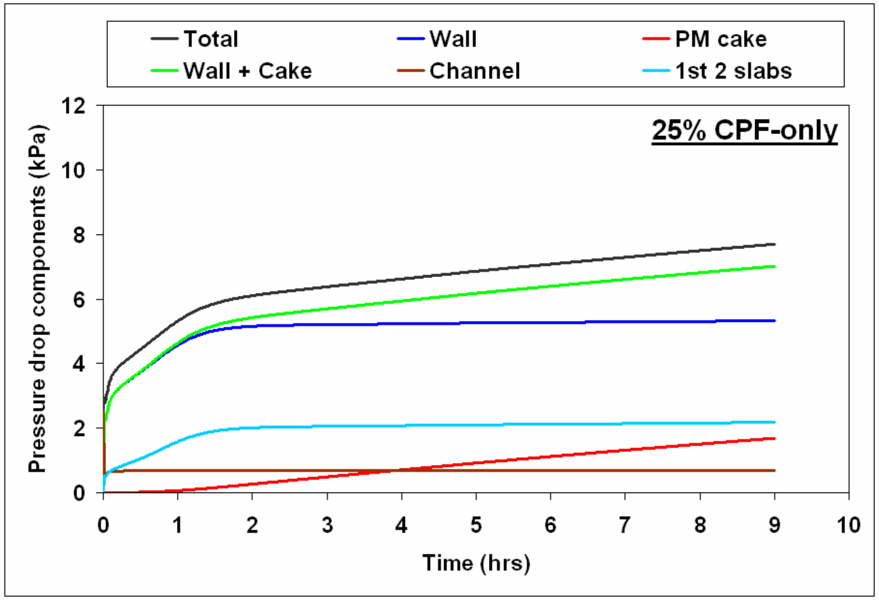
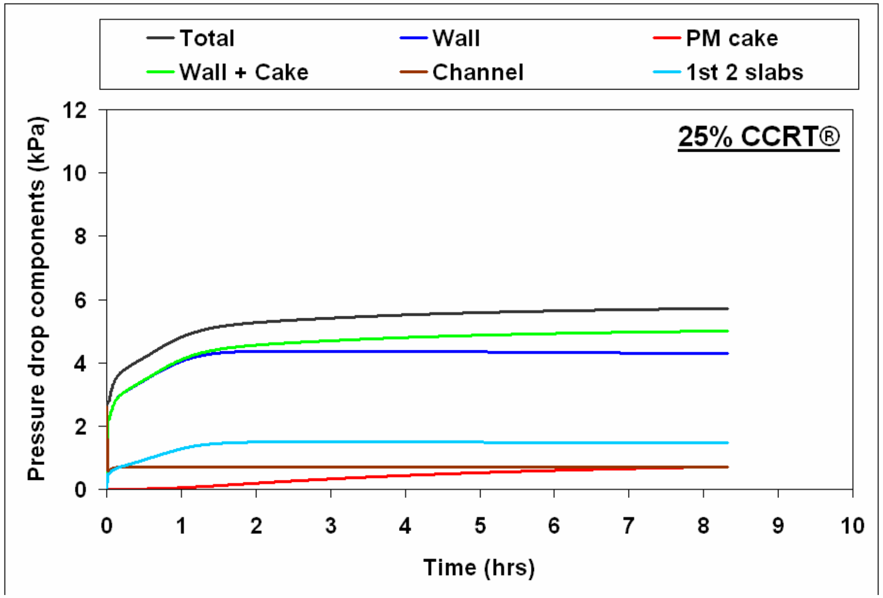
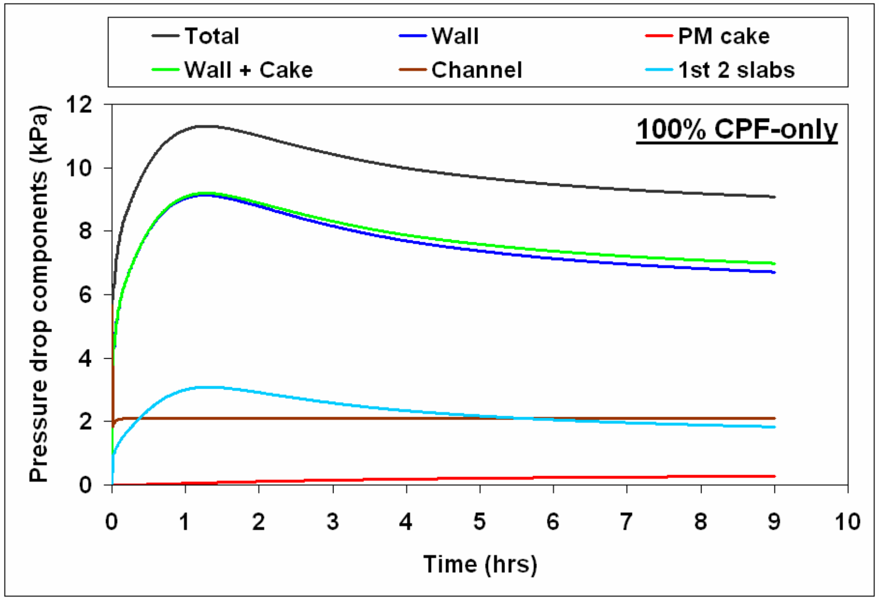
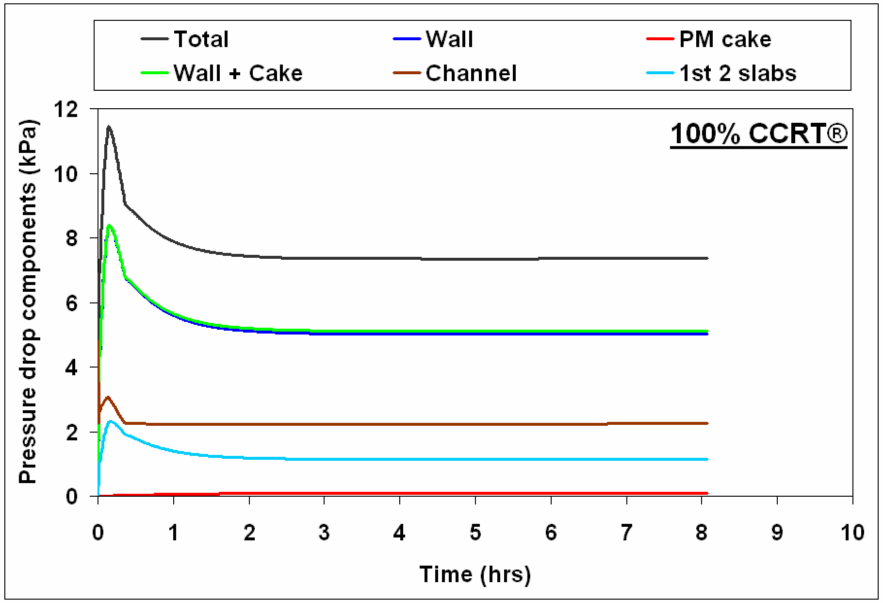
CPF Model Results – Pressure Drop Components

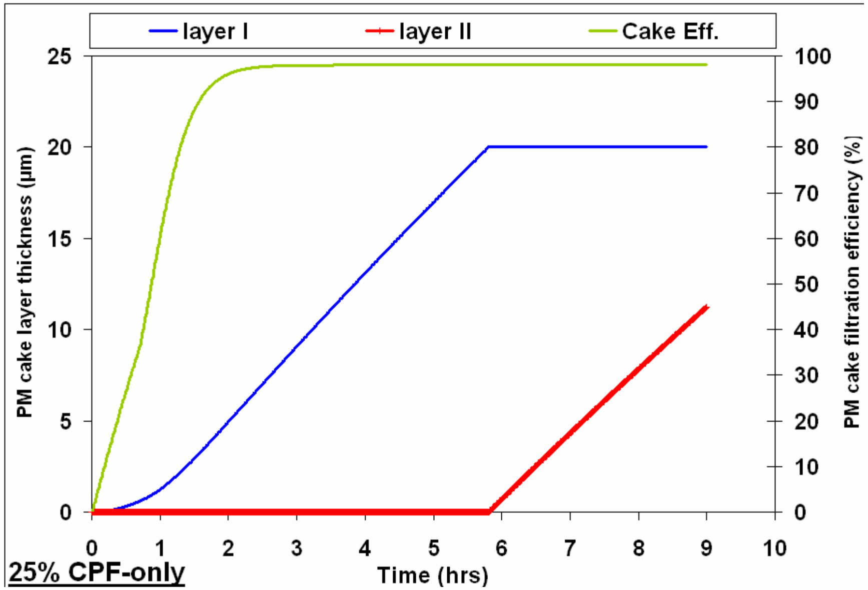




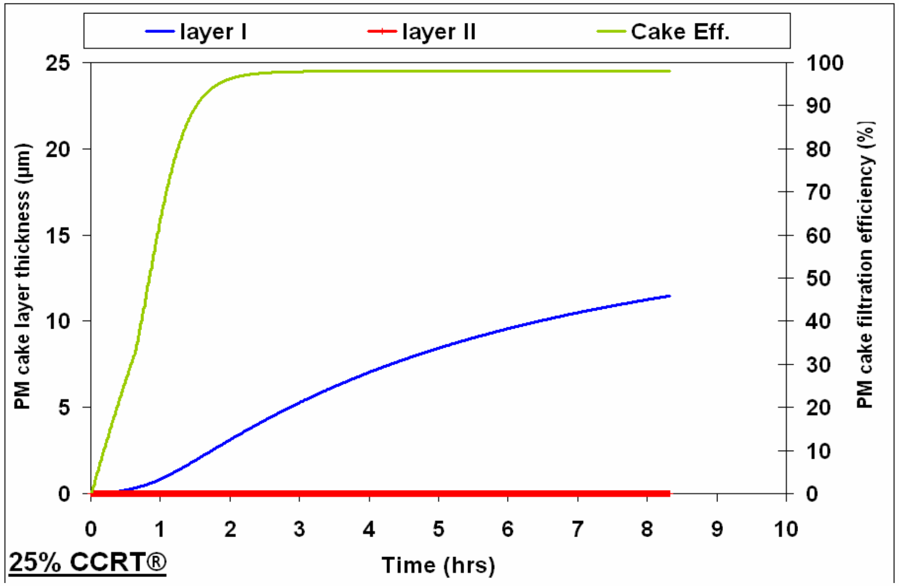




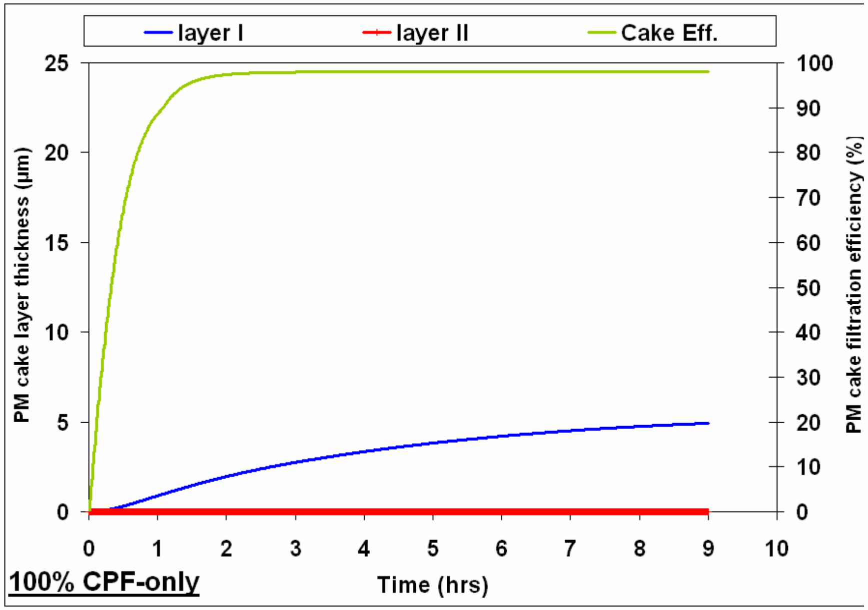
CPF Model Results – PM Cake Layer Thickness and Cake Efficiency



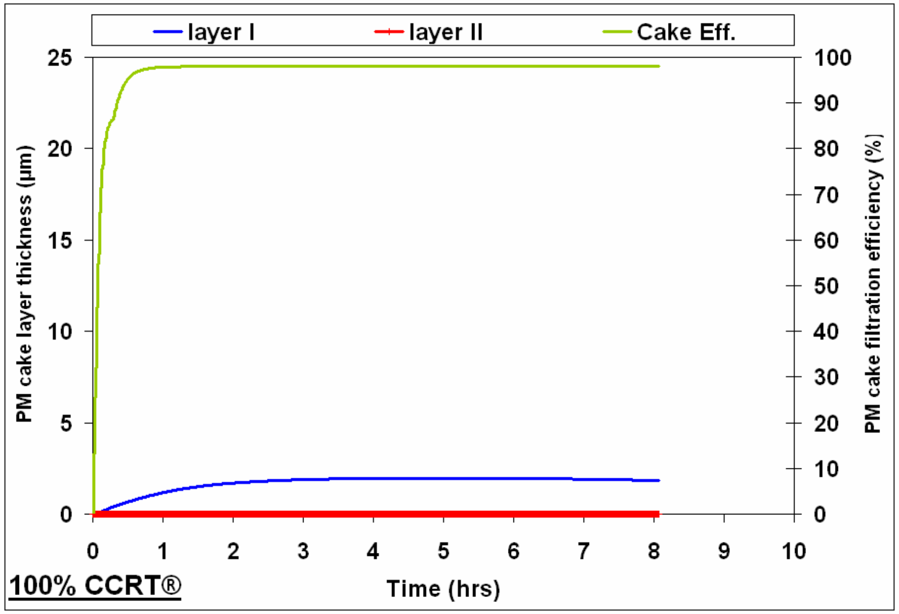
25% CPF-only



25% CCRT®

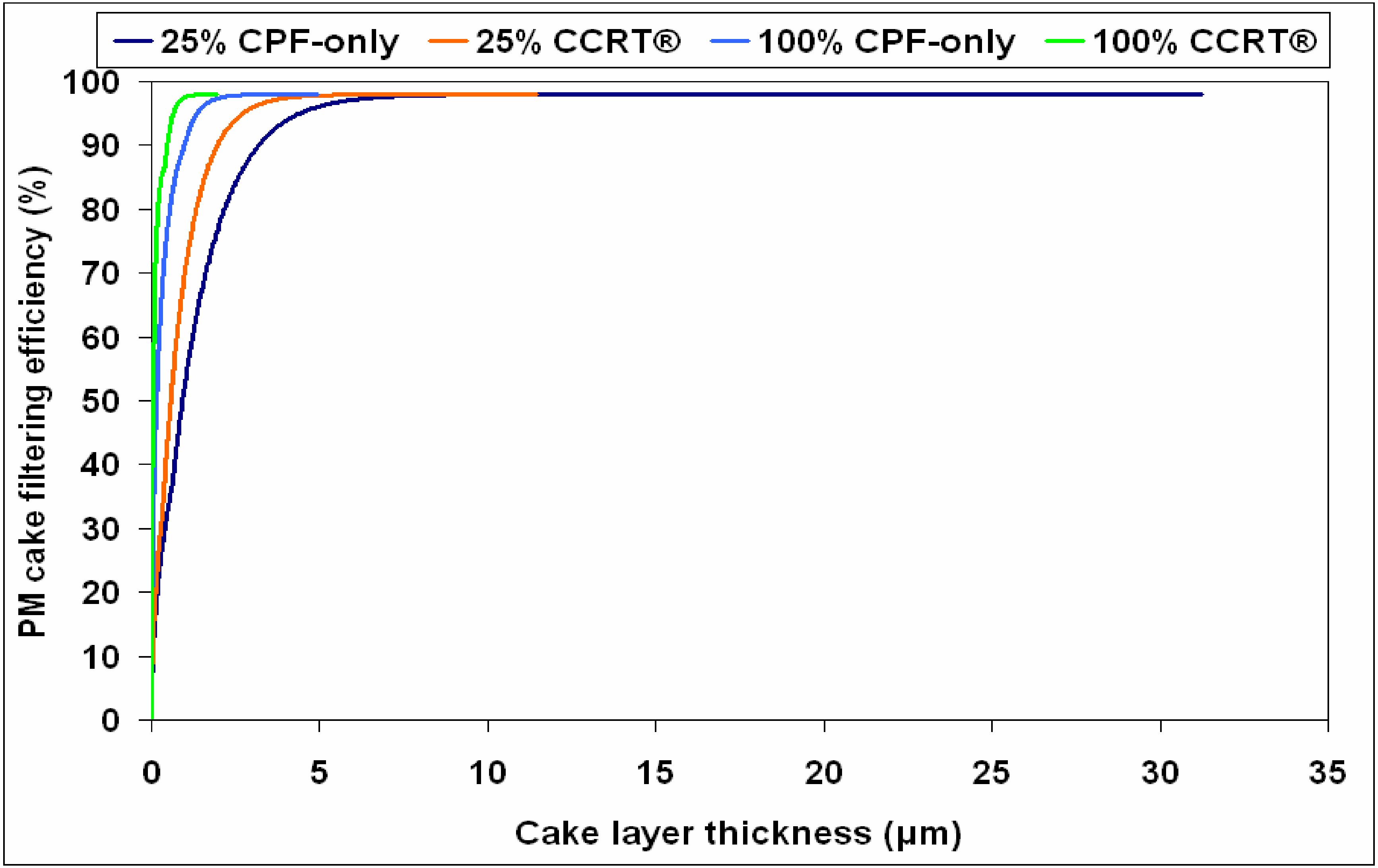


100% CPF-only



100% CCRT®

CPF Model Results – PM Cake Efficiency vs. Cake Layer Thickness



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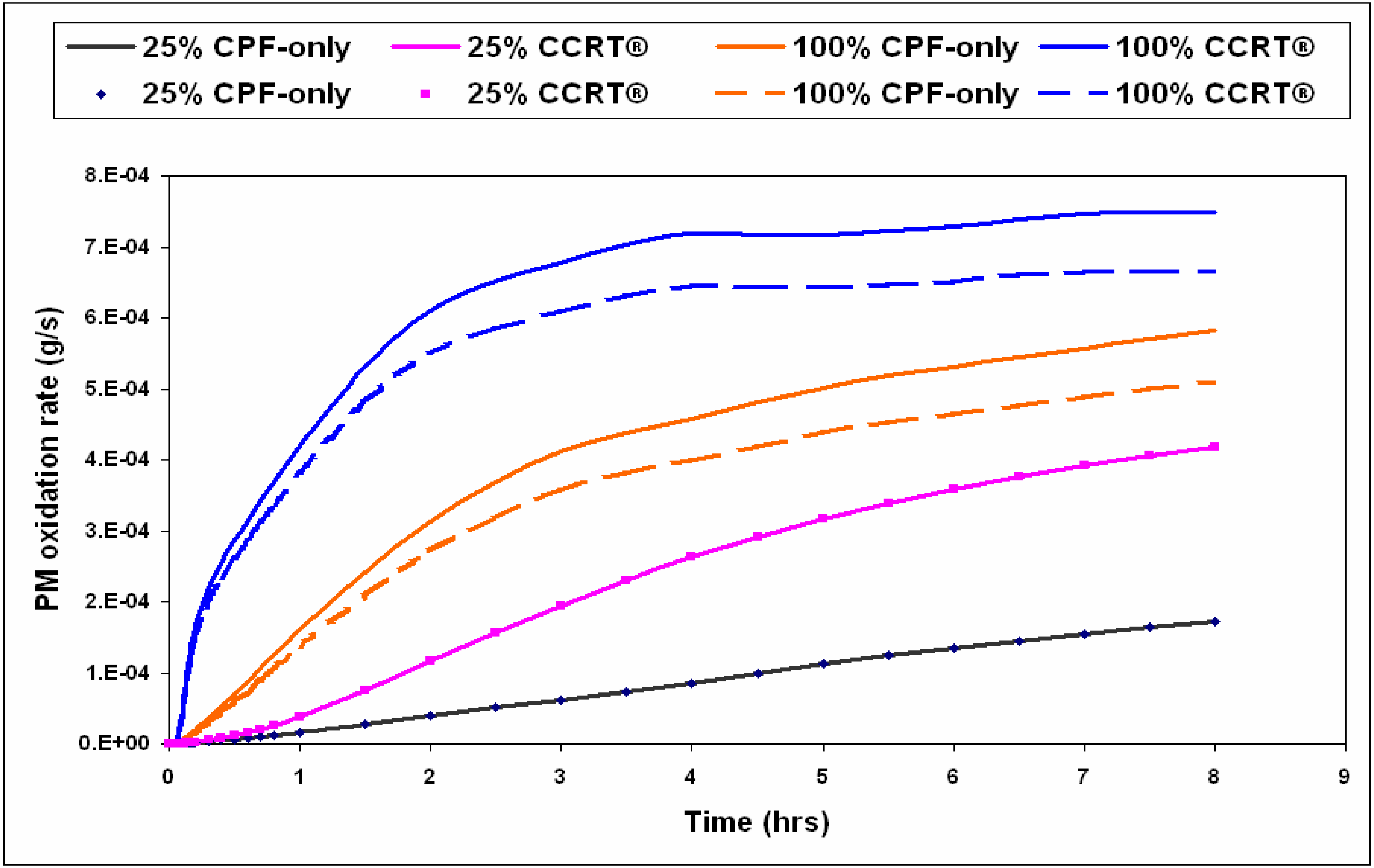
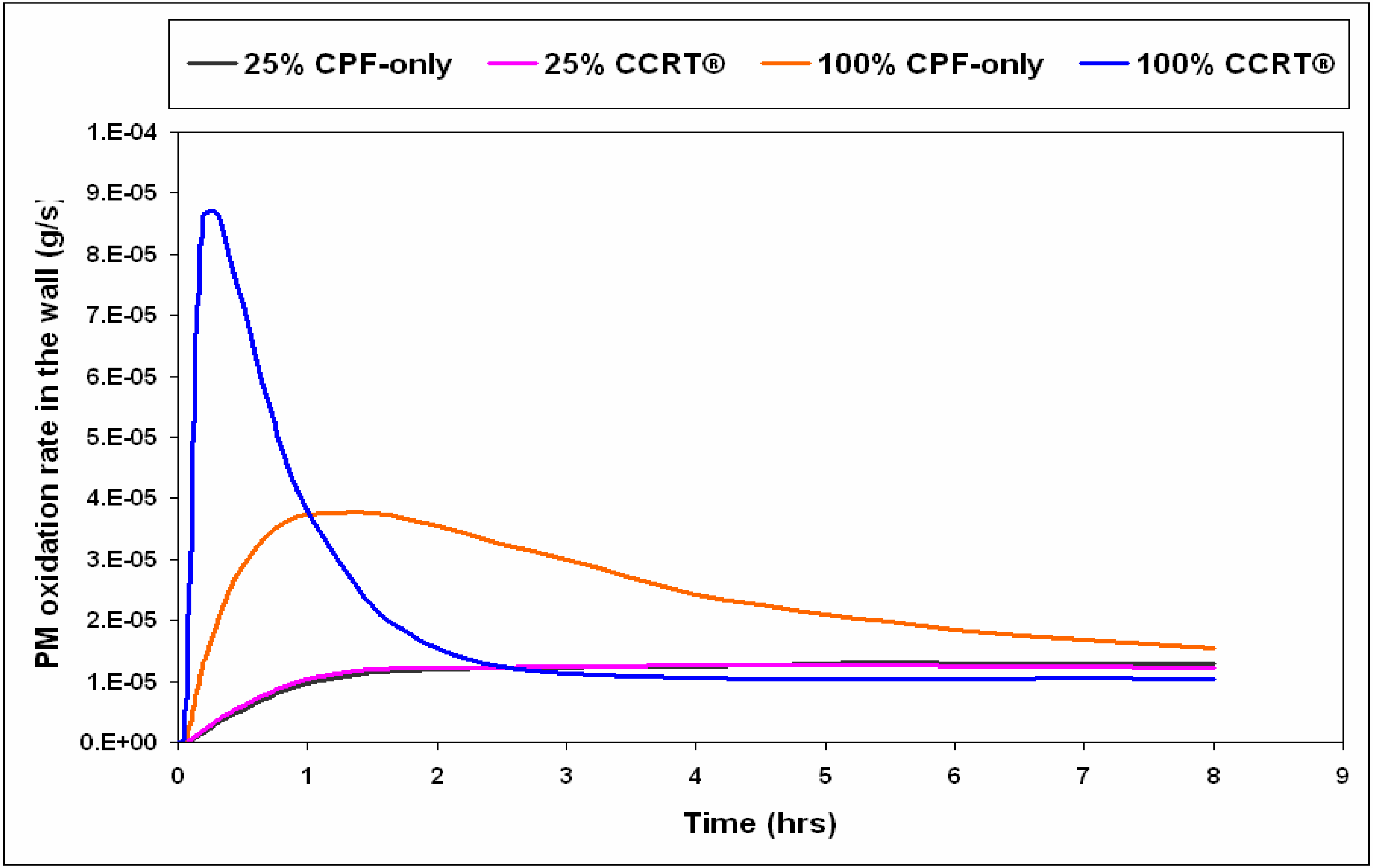
CPF Model Results – Total PM Oxidation Rates



CPF Model Results – Wall PM Oxidation Rates



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Filtration and Oxidation Characteristics of CPF (1 of 4)

PRESSURE DROP:

- Total CPF pressure drop increased with increasing loads due to higher exhaust flow rates.
- Pressure drop in the wall is principal contributor to total pressure drop.
- CPF pressure drop in 25% load case in both configurations increased steadily after PM cake layer efficiency exceeded 90% (95 minutes of loading time in CPF-only configuration and 92 minutes of loading time in CCRT® configuration), due to low wall and PM cake oxidation rates.
- CPF pressure drop in 100% load case in CCRT® configuration increased to a maximum of 12.2 kPa within 6 minutes of loading start and decreased to a “steady” value of 7.2 kPa, due to wall mass balance, i.e., PM oxidation rate in wall equals PM mass flow rate into wall from PM cake.

Higher loads produce higher ‘pressure drop spikes’, but regenerate the filter better due to higher CPF inlet temperatures and NO_2 flow-rates.

Filtration and Oxidation Characteristics of CPF (2 of 4)

PM OXIDATION:

- Higher % PM oxidized with increasing load, due to higher temperatures and higher NO_2 flow-rates.

- Catalytic PM oxidation mechanism was not necessary to model CPF oxidation behavior. Effect of catalyst would be to augment thermal/NO_2-assisted PM oxidation.

- NO_2 production in DOC helps in improving oxidation performance of CPF in CCRT® configuration, since % PM mass oxidized were always higher in CCRT® configuration compared to CPF-only configuration.

- No/low effective NO_2 production in CPF was observed in this research. NO_2 consumption due to PM oxidation reaction is being accounted for in the model, but consumption of NO_2 observed is greater than result of this effect.

Filtration and Oxidation Characteristics of CPF (3 of 4)

FILTRATION EFFICIENCY:

- Overall CPF filtration efficiencies were in the 99.5-99.8% range (on a total PM volume concentration basis).

- PM cake is the primary filter, after it is formed. Over 90% cake filtration efficiency was observed when PM cake is 2 µm in 25% load case, and 1 µm in 100% load case in CCRT® configuration.

- Filling of PM in wall results in transition region, followed by PM cake formation.

- Wall filtration efficiency decreases with increasing wall oxidation, but does not affect overall efficiency because of presence of PM cake filter, with 98% overall filtration efficiency when the cake layer thickness is greater than 1–2 µm.

Filtration and Oxidation Characteristics of CPF (4 of 4)

Overall, the phenomena that are taking place with progression of loading time (in order mentioned) are:

- PM accumulation in wall,
- Cake formation due to filling up of voids in wall,
- Cake becoming first filter in series with wall,
- In 100% load case, wall PM oxidation rate is greater than PM deposition in the wall, hence wall (and so, overall) pressure drop decreases and eventually reaches ‘steady’ state.
- In 25% load case, cake pressure drop increases steadily, while wall pressure drop remains constant due to constant mass of PM in the wall.

Questions