Asymmetric and Variable Cell Geometry Diesel Particulate Filters

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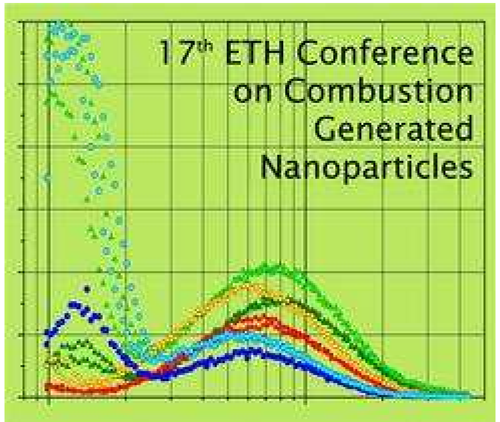
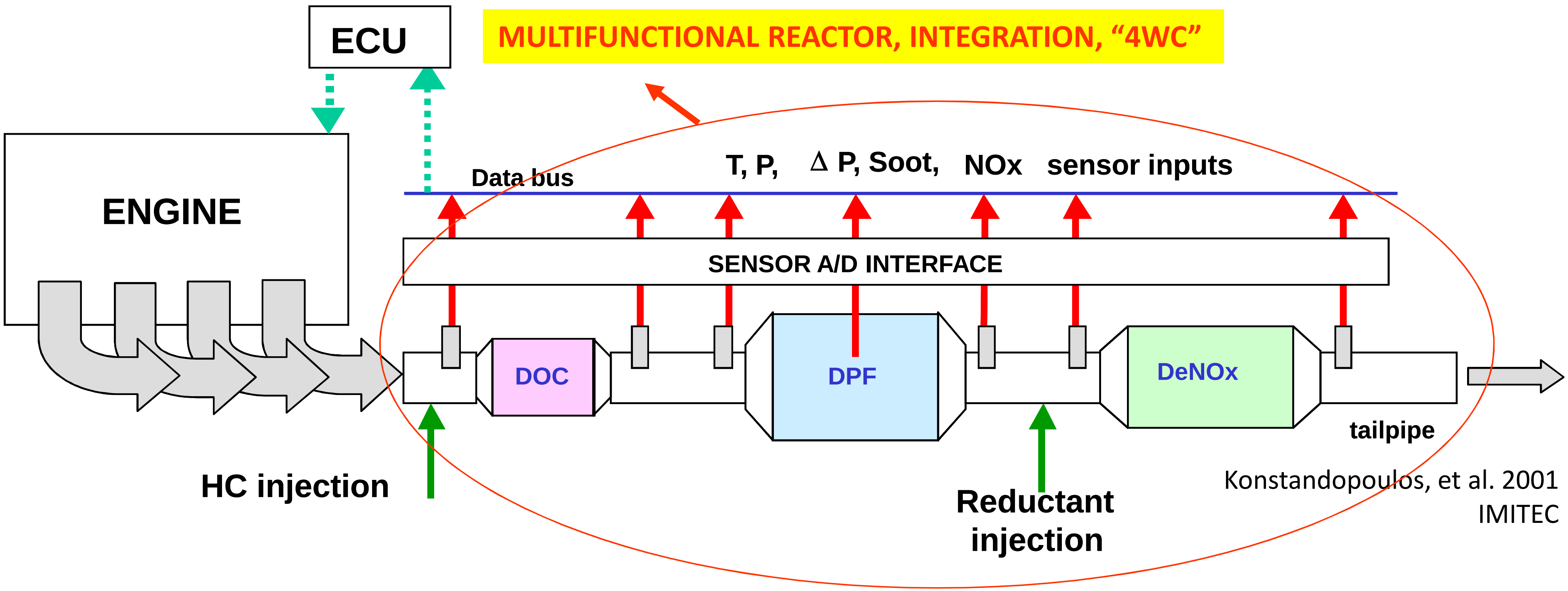


Outline

- **Motivation**
- **Theoretical Analysis**
  Pressure drop and soot deposit growth
- **Validation with Experiments**
- **Conclusions**

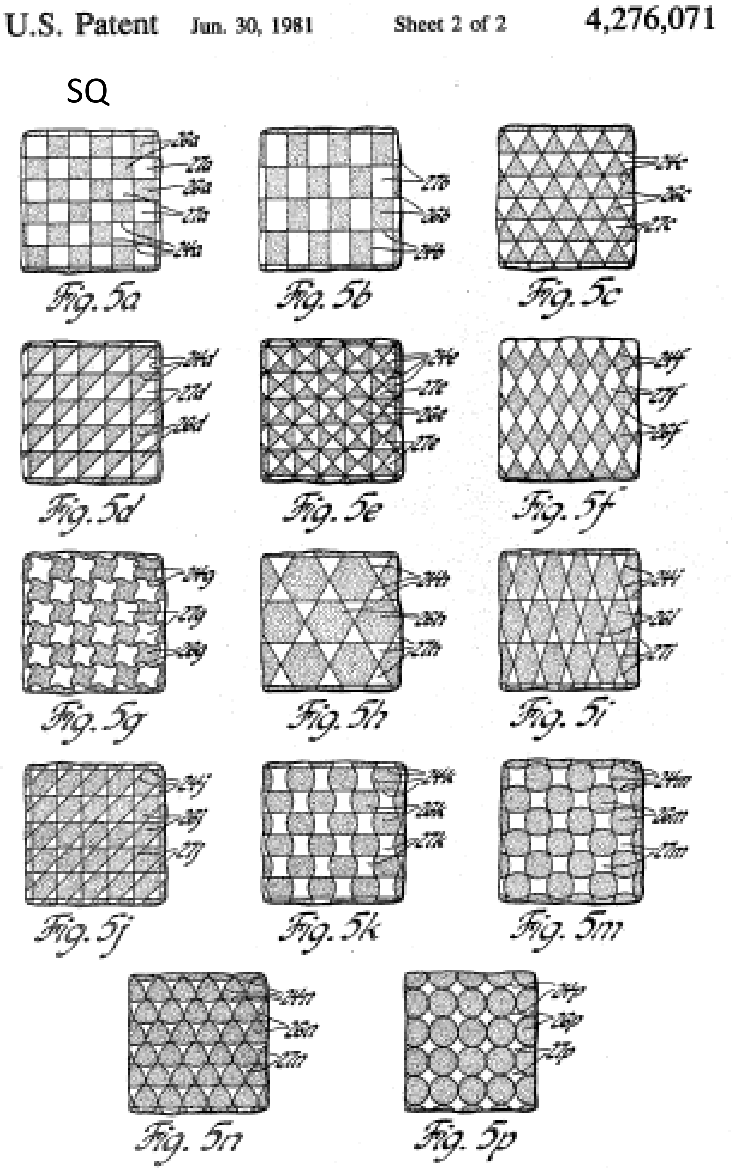
Emission Control: A Chemical Plant in the Exhaust



- **Adding devices** = more pressure drop, more space in system layout
- **Increasing catalyst loads** = more pressure drop, less space in device
  - ✓Optimization requires overcoming these constraints
  - ✓Focus on **cell geometry and layout**

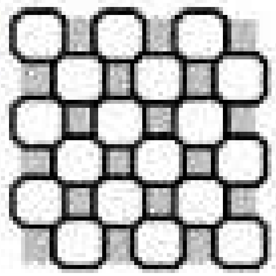
Evolution of DPF Cell Geometries

SQ



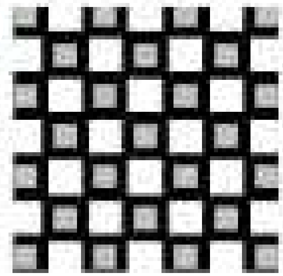
ASYMMETRIC DESIGNS

OS



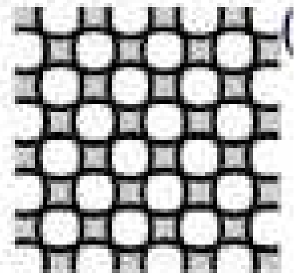
Ogyu et al
SAE 2004-01-0949

ACT



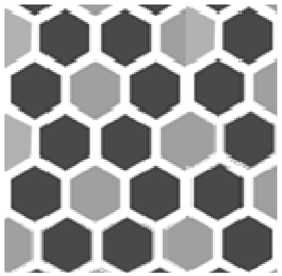
Young et al
SAE 2004-01-0948

WAVY



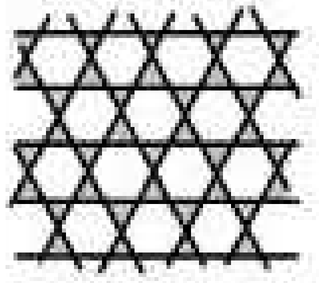
Bardon et al
SAE 2004-01-0950

HEX



Iwasaki, et al
SAE 2012-01-0838

HEX-TRIANG

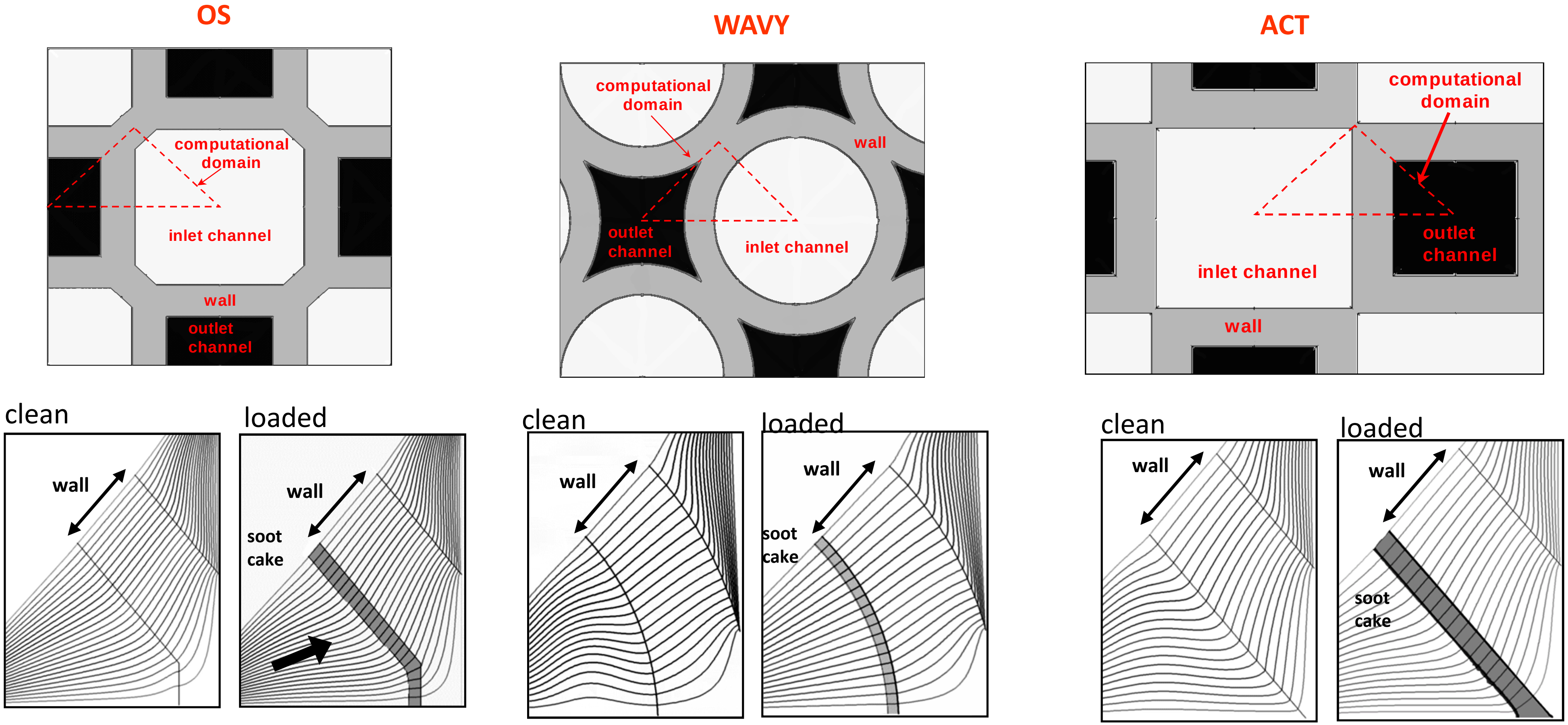


dieselnet.com

NEW DESIGNS?

Flow Re-adjustment in Asymmetric Cells

Konstandopoulos et al, SAE 2005-01-0946



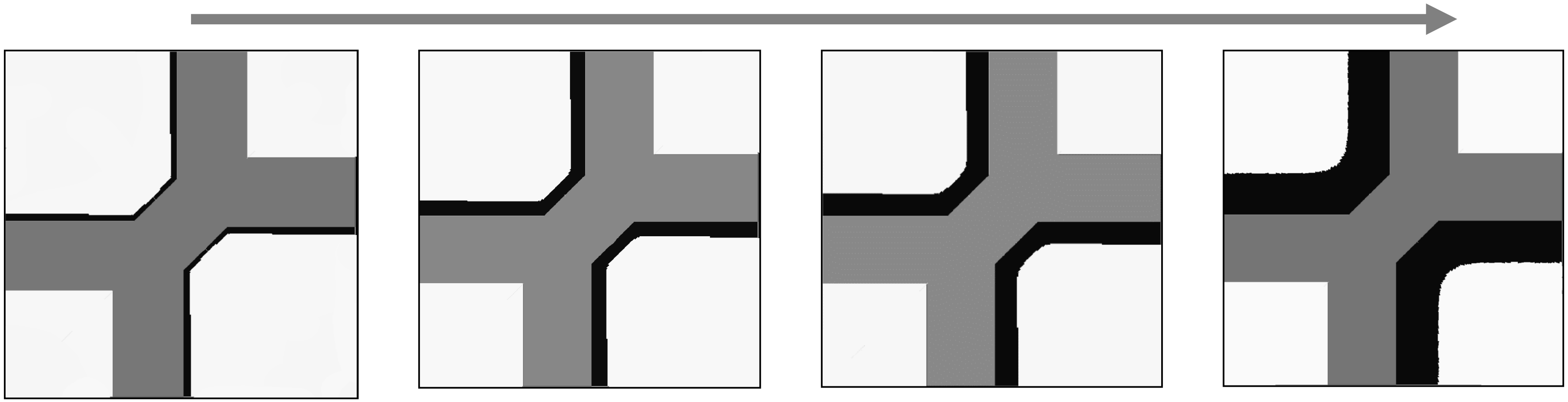
- Flow continuously readjusts according to the wall resistances
- Soot deposits form on all walls

Flow Re-adjustment in Asymmetric Cells

Clean filter **Loaded filter**

Konstandopoulos et al, SAE 2005-01-0946

Time



- Follow up studies (e.g. Wurzenberger et al SAE 2007-01-1137, Tang et al SAE 2009-01-127, Aravelli et al 2007-01-0920) have addressed modeling aspects of asymmetric cell DPFs, with varying degrees of simplification.
- In all cases a *single valued "wall/filtration velocity"* is adopted without explicit considerations of additional flow paths over the cell geometry.

Cell Geometries Studied

Same inlet and outlet cell

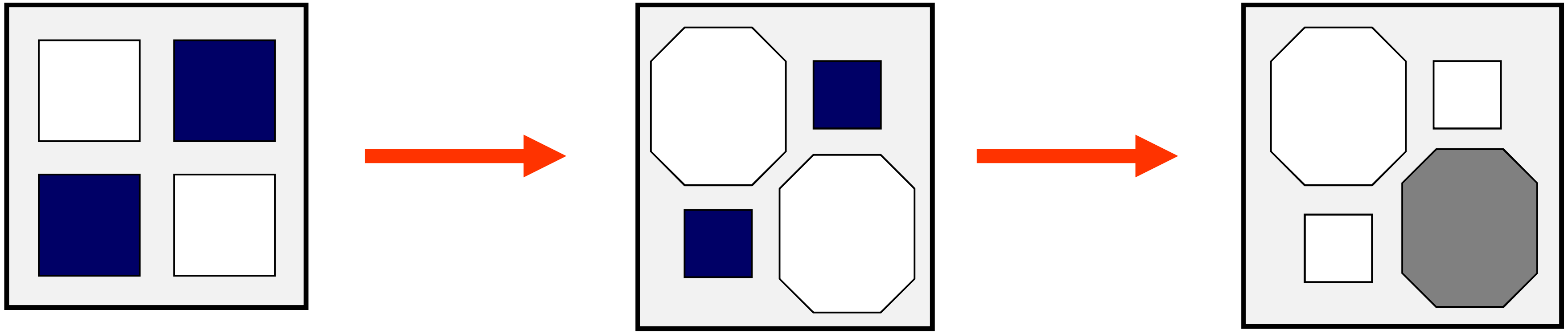
1 type of inlet
1 type of outlet cells

2 types of inlet
1 type of outlet cells

Square

Octo-Square

"Valuable Plugging Layout"



SQ

OS

Ogyu et al
SAE 2004-01-0949

VPL

Nakamura et al
SAE 2014-01-1512

General model for VPL which can be reduced to one for OS

Model Formulation: Two Types of Inlet Channels-1

Exhaust gas mass balances for each channel (1, 2, 3)

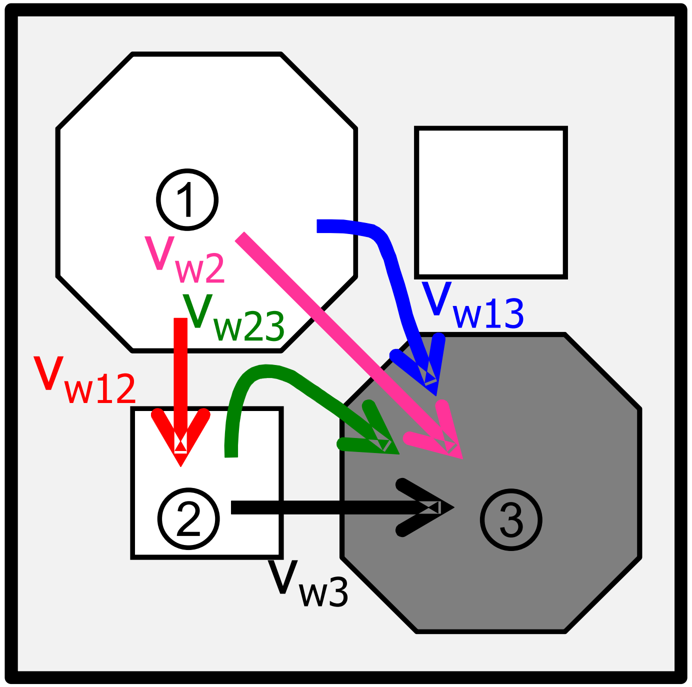
$$A_1 \frac{\partial u_1}{\partial z} = -\Pi_1 v_{w12} - \Pi_1 v_{w13} - \Pi_2 v_{w2}$$

$$A_2 \frac{\partial u_2}{\partial z} = \Pi_1 v_{w12} - \Pi_1 v_{w23} - \Pi_3 v_{w3}$$

$$A_3 \frac{\partial u_3}{\partial z} = \Pi_1 v_{w13} + \Pi_2 v_{w2} + \Pi_1 v_{w23} + \Pi_3 v_{w3}$$

where u_1, u_2, u_3 are the cross section averaged velocities

5 flow paths/velocities



Axial Momentum Balances for each channel (1, 2, 3)

$$\frac{\partial P_1}{\partial z} = -\alpha_1(t)\mu u_1 \frac{A_1}{A_{1t}(t)}$$

$$\frac{\partial P_2}{\partial z} = -\alpha_2(t)\mu u_2 \frac{A_2}{A_{2t}(t)}$$

$$\frac{\partial P_3}{\partial z} = -\alpha_3 \mu u_3$$

Π_i: Perimeter of each channel, i

A_i : Cross section of each channel, $A_{it}(t)$: evolving area of cell

$\alpha_i(t)$: Evolving friction coefficient of each cell

Model Formulation: Two Types of Inlet Channels-2

Wall Momentum Balances (Pressure Drop through each flow path)

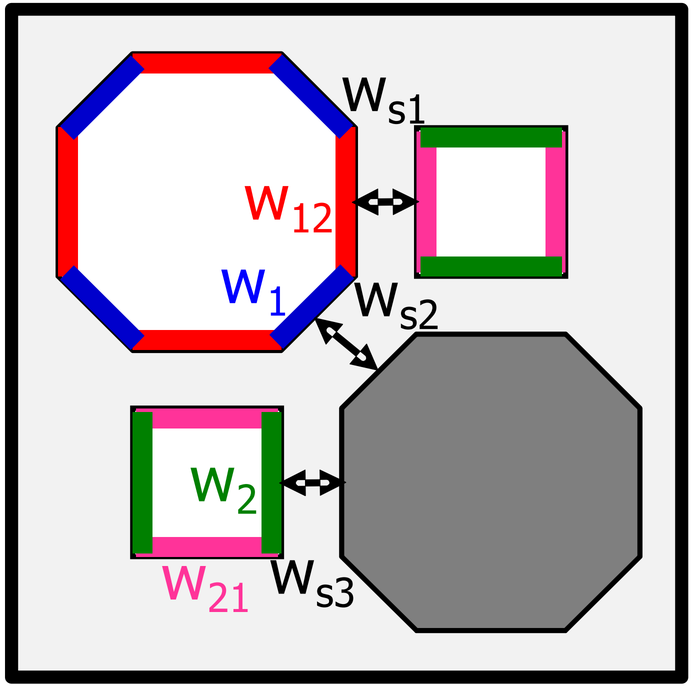
$$v_{w12} = \left(\frac{\mu w_{s1} k_w}{k_w} + \frac{\mu (w_{12} + w_{21})}{k_s}\right)^{-1} (P_1 - P_2)$$

$$v_{w13} = \left(\frac{\mu w_{eff}}{k_w} + \frac{\mu w_{12}}{k_s}\right)^{-1} (P_1 - P_3)$$

$$v_{w2} = \left(\frac{\mu w_{s2}}{k_w} + \frac{\mu w_1}{k_s}\right)^{-1} (P_1 - P_3)$$

$$v_{w3} = \left(\frac{\mu w_{s3}}{k_w} + \frac{\mu w_2}{k_s}\right)^{-1} (P_2 - P_3)$$

$$v_{w23} = \left(\frac{\mu w_{eff}}{k_w} + \frac{\mu w_{21}}{k_s}\right)^{-1} (P_2 - P_3)$$



w_{eff}: is determined by a separate flow problem over the wall cross-section

Model Formulation: Two Types of Inlet Channels-3

Soot Deposits Evolution

$$\frac{\partial w_{12}}{\partial t} = \frac{v_{w1}\rho_g \varphi_1}{\rho_s}$$

$$\frac{\partial w_{21}}{\partial t} = \frac{\Omega(-v_{w12} + v_{w23})\rho_g \varphi_2}{\rho_s}$$

$\Omega(x)=x$ for $x>0$ and $\Omega(x)=0$ for $x \le 0$.

$$\frac{\partial w_{1}}{\partial t} = \frac{v_{w2}\rho_g \varphi_1}{\rho_s}$$

$$\frac{\partial w_{2}}{\partial t} = \frac{v_{w3}\rho_g \varphi_2}{\rho_s}$$

Soot Transport and Deposition

$$A_1 u_1 \frac{\partial \varphi_1}{\partial z} = -\varphi_1 \Pi_1 \Omega(-(v_{w12} + v_{w13}))$$

$$A_2 u_2 \frac{\partial \varphi_2}{\partial z} = -\varphi_2 \Pi_2 U(v_{w12} - v_{w23})$$

$\phi 1, \phi 2$: the local soot mass fraction in gas phase

Cell cross-section evolution

$$A_{1t}(t) = A_1 - \Pi_1 w_1 - \Pi_2 w_2$$

$$A_{2t}(t) = A_2 - \Pi_1 w_{r1} - \Pi_3 w_3$$

Boundary conditions

$P_3 = P_{atm}$ at $z=L$,

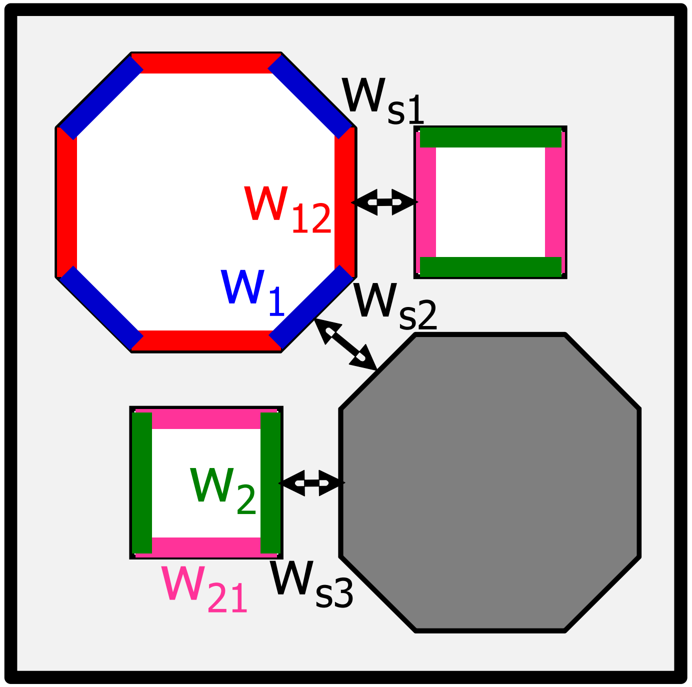
$A_1 u_1 + A_2 u_2 = (A_1 + A_2) u_o$,

$\varphi_1 = \varphi_2 = \varphi_{in}$ at $z=0$

where

u_o is the average inlet velocity

ϕ_{in} is the inlet soot mass fraction.

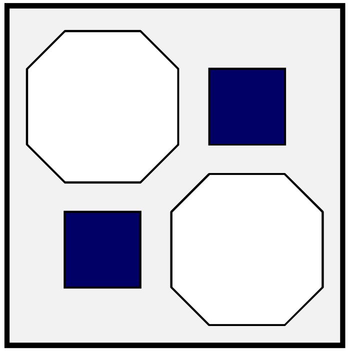


Solution procedure

- Outer initial value problem (evolution equations of the deposits) explicit intefration
- Inner boundary value problem (flow and soot transport) solved at each step of outer problem, fulfilling BC with Newton-Raphson
- Advance soot deposit thickness and evolve cross section

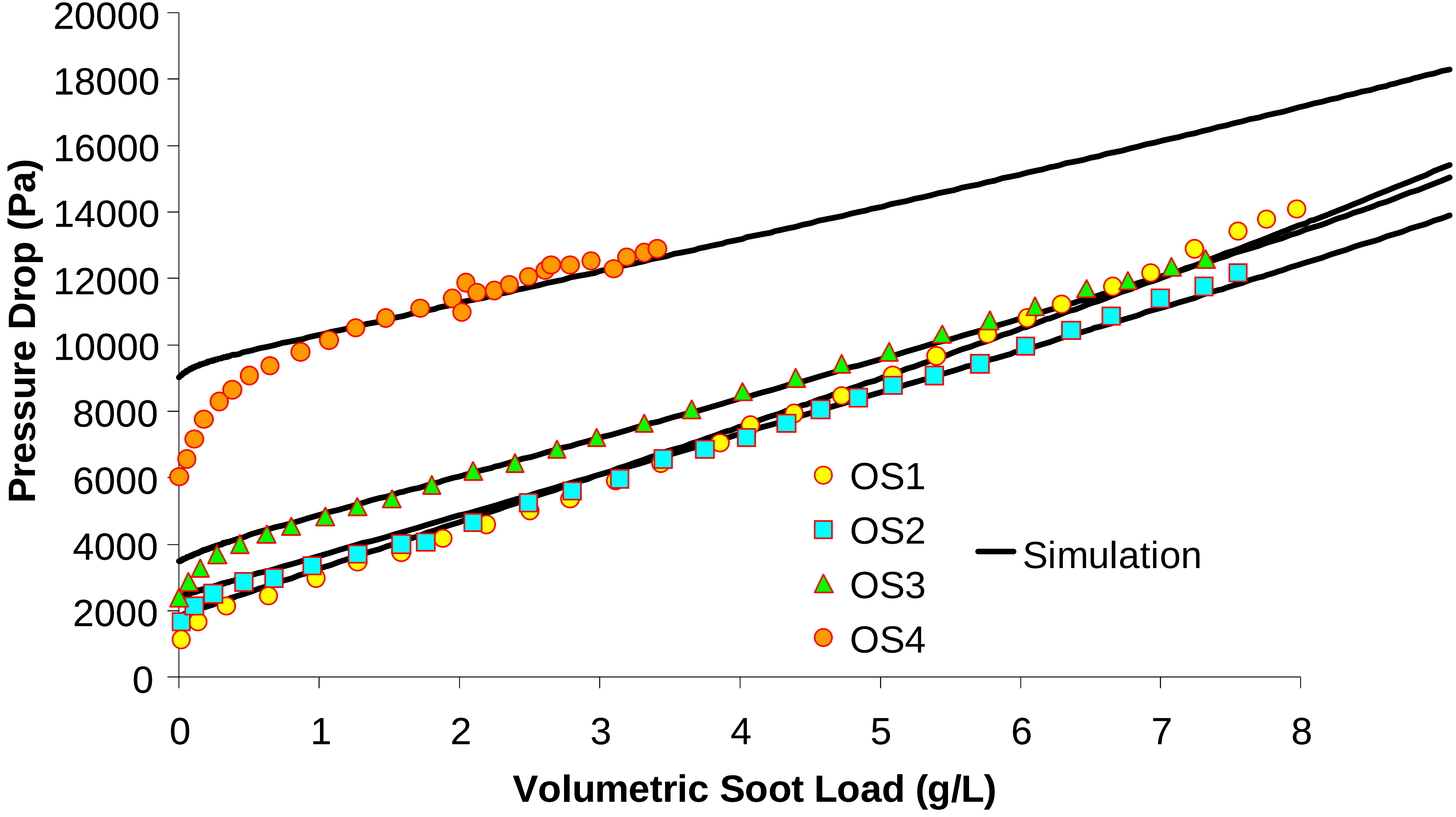
Samples Used for Validation – 4 OS DPFs

FILTER TYPE	OS	OS1	OS2	OS3	OS4
Diameter	mm	143.8	143.8	143.8	143.8
Length	mm	150.0	150.0	150.0	150.0
Wall permeability (x1E12)	m^2	1.00	1.00	1.00	3.00
Oct-Sq wall thickness, w1	mm	0.4	0.4	0.4	0.4
Oct-Oct wall thickness, w2	mm	0.4	0.4	0.4	0.4
Oct side, C_{w1}	mm	1.77	1.96	2.17	2.44
Sq side, C_{w2}	mm	1.42	1.23	1.02	0.75

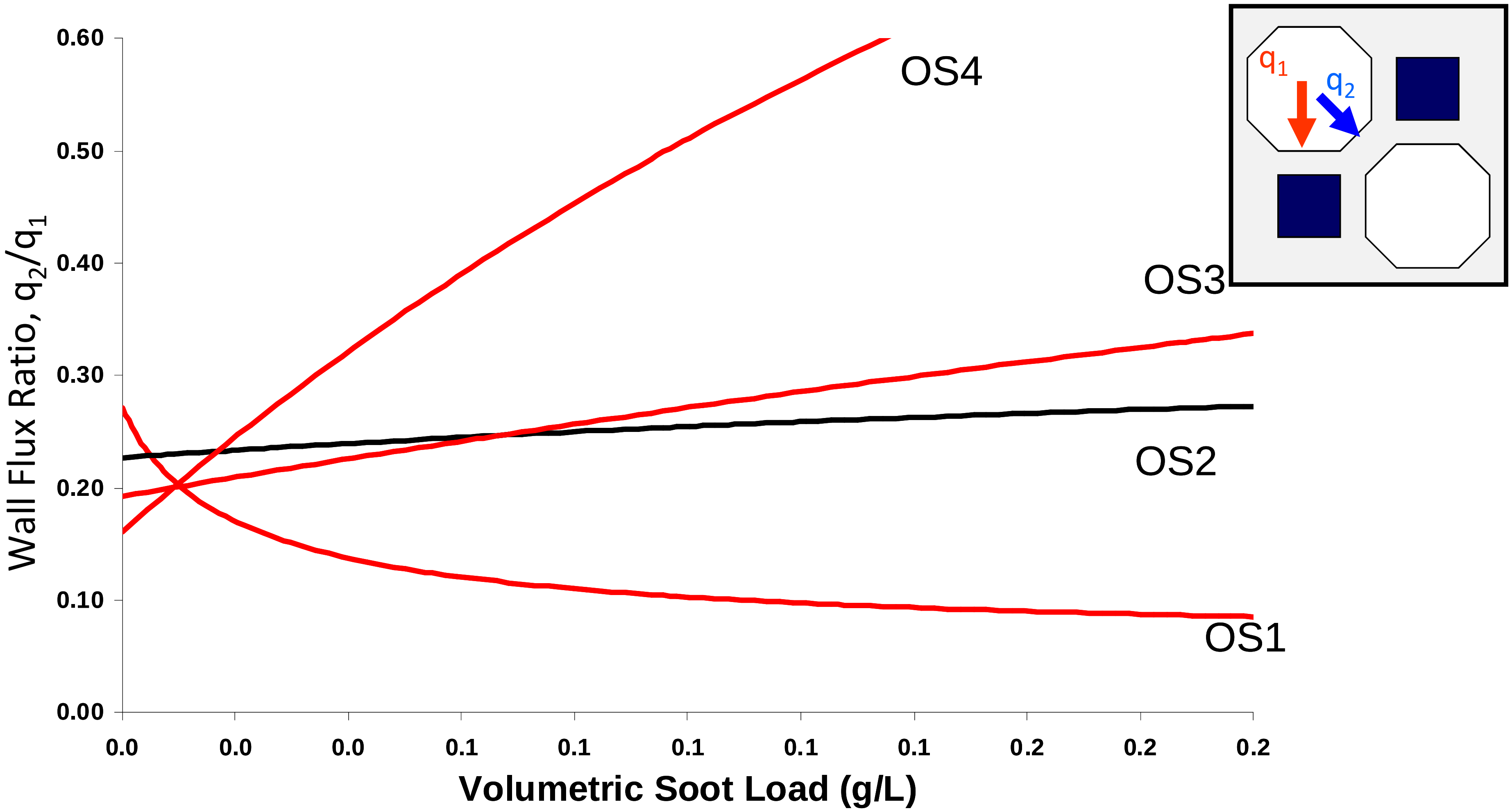


Soot loading of OS samples: Experiment and Model

Deep bed calculation not-included to see intrinsic curvature effects of Pressure Drop curve

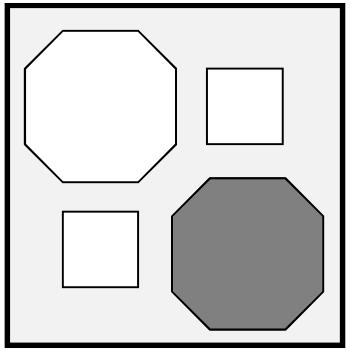


Evolution of Wall Mass-Flux Ratio: (O to O /O to S)

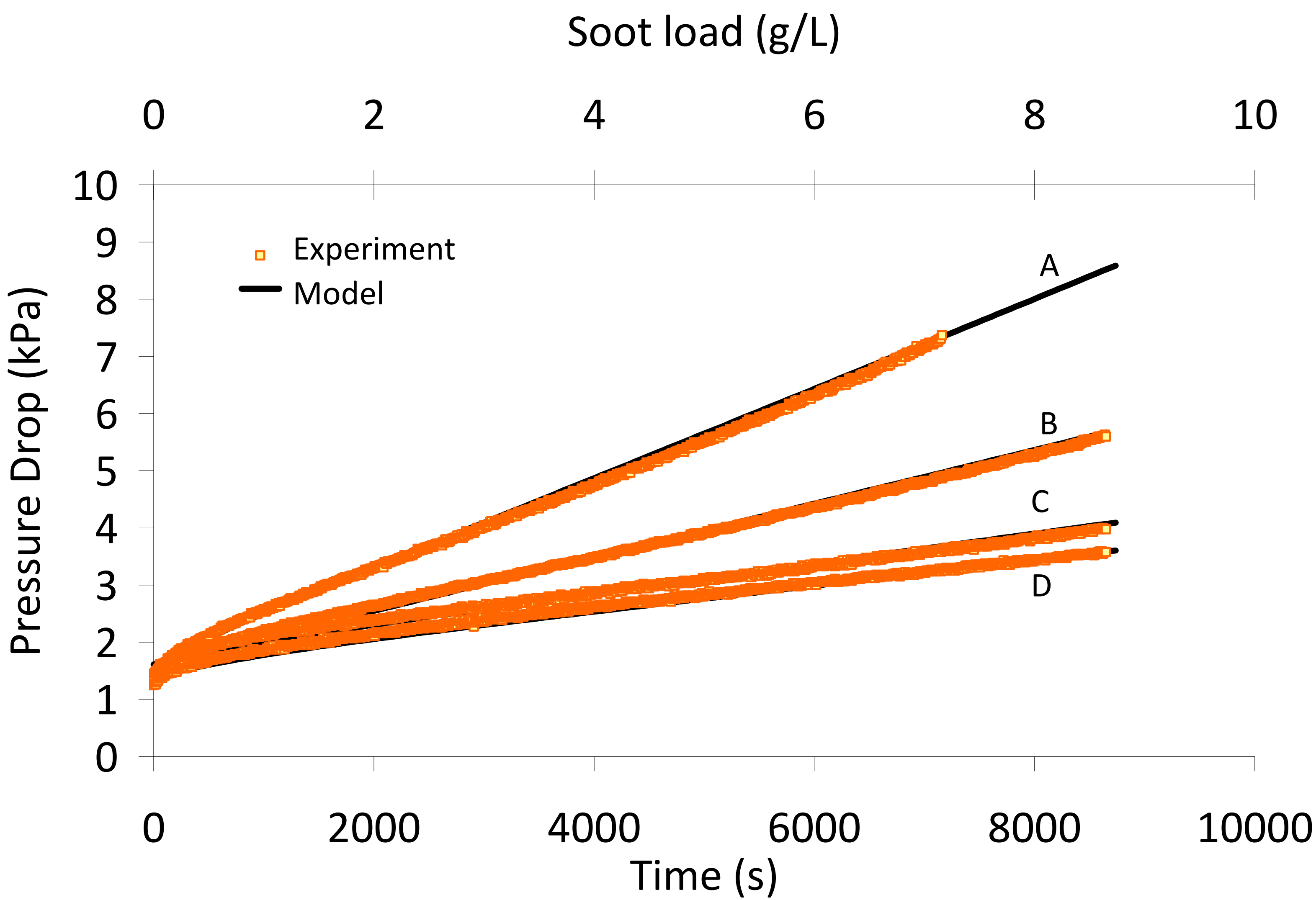


Samples Used for Validation – 4 VPL DPFs

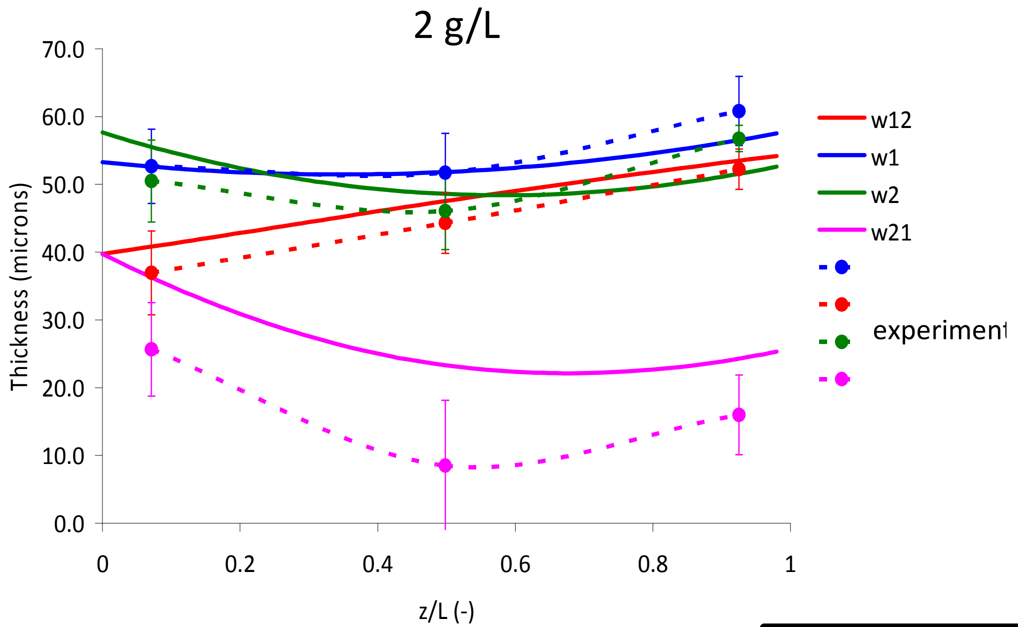
FILTER TYPE	VPL	A	B	C	D
Diameter	mm	143.8	143.8	143.8	143.8
Length	mm	108.0	140.5	193.2	193.2
Wall permeability (x1E13)	m^2	4.00	4.00	3.203	3.203
Oct-Sq wall thickness, w_1	mm	0.254	0.254	0.254	0.176
Oct-Oct wall thickness, w_2	mm	0.359	0.359	0.359	0.251
Oct side, C_{w1}	mm	1.497	1.497	1.497	1.575
Sq side, C_{w2}	mm	0.962	0.962	0.962	1.039

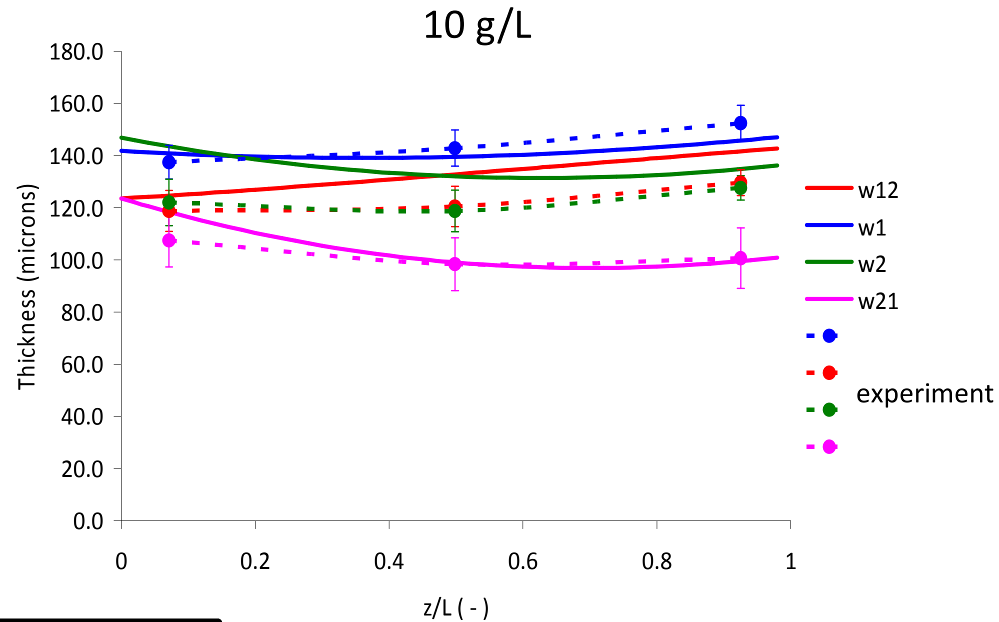


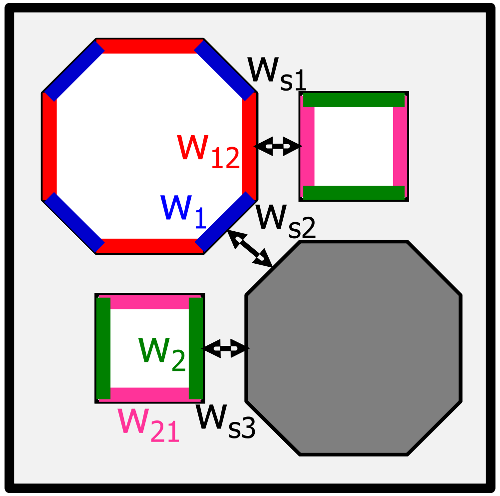
Soot loading of VPL samples: Experiment and Model



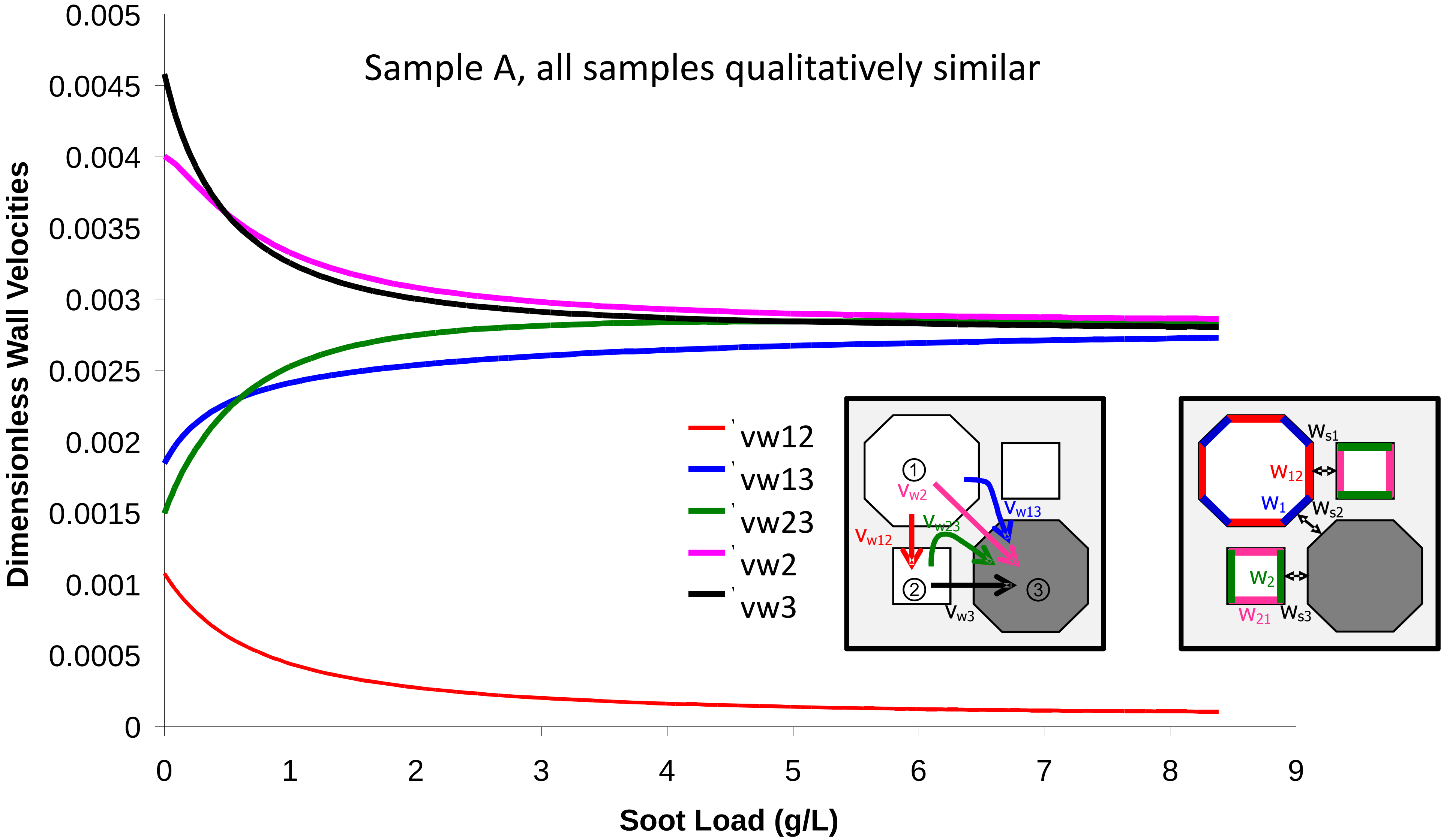
Soot deposits of VPL samples: Experiment and Model



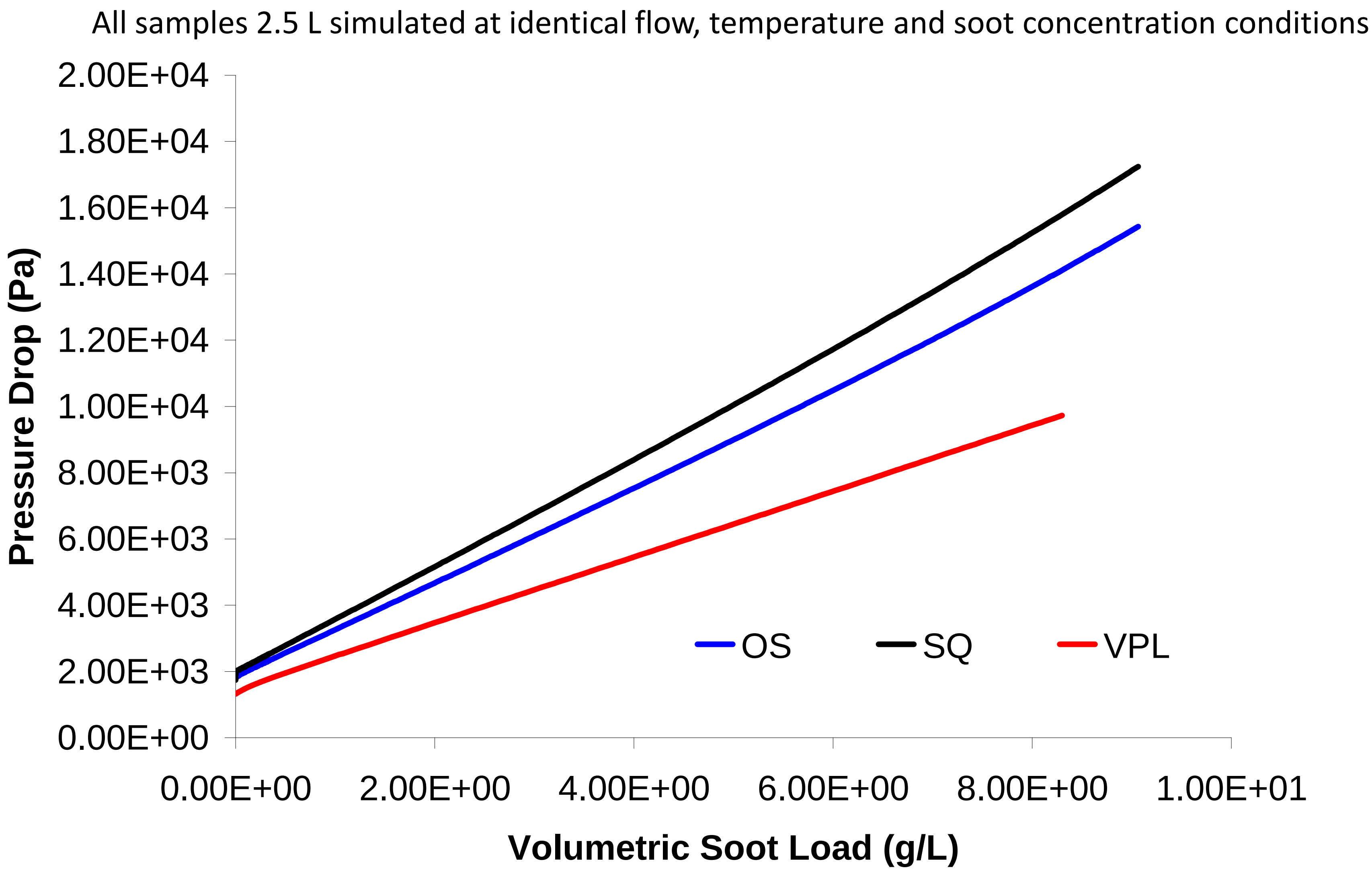




Evolution of filtration velocities in VPL DPF



Optimization of DPF designs for constant volume



Conclusions

- Asymmetric and Variable Cell geometry DPFs introduce **many complexities** into the standard simulation framework of DPFs by requiring the explicit treatment of **additional flow paths** in order to properly capture the flow dynamics through the structure.

- Relevant wall fluxes and velocities have been identified and simulated. Their evolution at long times (high values of soot loafing) indicates that **in the case of OS design a constant wall flux ratio is established and can be used as a metric to select DPFs with lower pressure drops**. In the more complex case of the **VPL design a clustering of all but one filtration velocity towards a common value** is observed as a result of the complex interactions among the different flow paths.

- Pressure drop in the OS and VPL DPFs still follows **a linear evolution with respect to soot load** as the different flows through the common (inlet-inlet) and conventional (inlet-outlet) flow paths **readjust to transport and deposit the soot particles through the path of least resistance**.

- The advent of AVC DPF designs with many degrees of freedom with respect to filtration/wall velocities, **leads to DPF systems with substantially reduced pressure drop compared to the state-of-the-art**.

Acknowledgements

We thank Ibiden Co. for making available the experimental data on the OS and VPL DPF designs.

WORKSHOP ANNOUNCEMENT- Oct. 16-17, 2014

http://aptstep.certh.gr

aptSTEP WORKSHOP 1

Combustion Emission Control for Clean and Efficient Vehicles

October 16-17, 2014
Thessaloniki, Greece

TOPICS of INVITED LECTURES

Future Fuels - Future Engines
Multifunctional Emission Control Devices
Challenges in Low Emissions Measurement & Testing
Air Quality Issues and Retrofit Approaches

New Journal from Springer

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Thank you for your attention!

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