Modeling Pressure Drop of Wall-Flow Diesel Particulate Filters

Part 2: Model for Soot-Loaded Filters

Mansour Masoudi

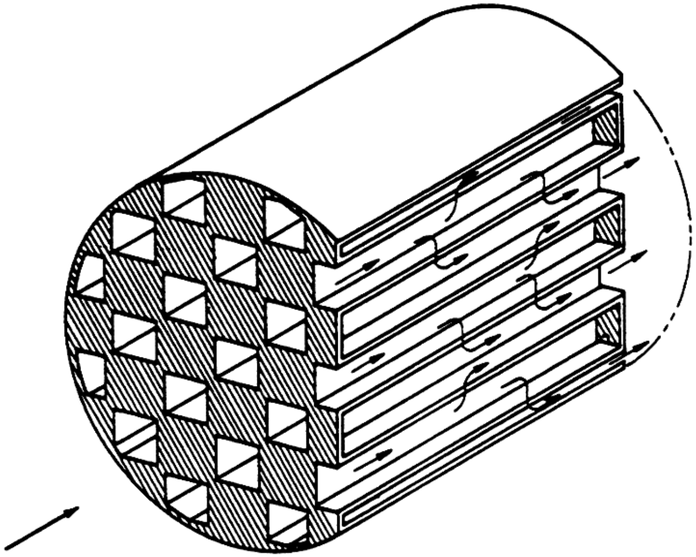
October 2001, Detroit, MI

CLEERS NOx Trap / DPF Modeling Workshop

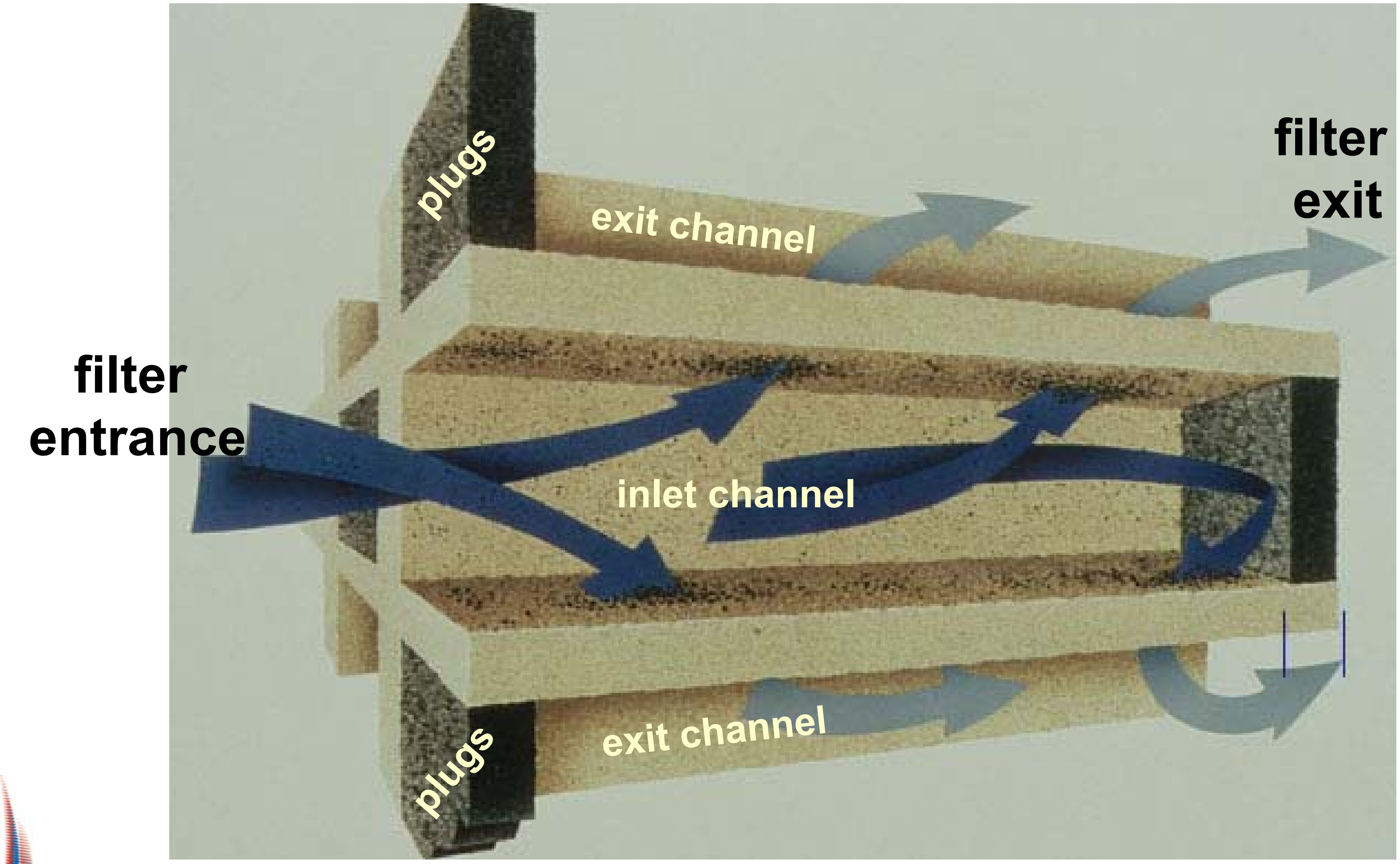
CORNING
Discovering Beyond Imagination

DPF Pressure Drop -- Highlight

- DPF "***pressure drop***" is the manifestation of ***<u>Hydrodynamic</u>*** response of *honey comb* structure to exhaust gas flow *<u>through</u>* it.
- A ***hydrodynamic (fluid mechanics)*** *problem.*
- ***"Internal flow"*** type.

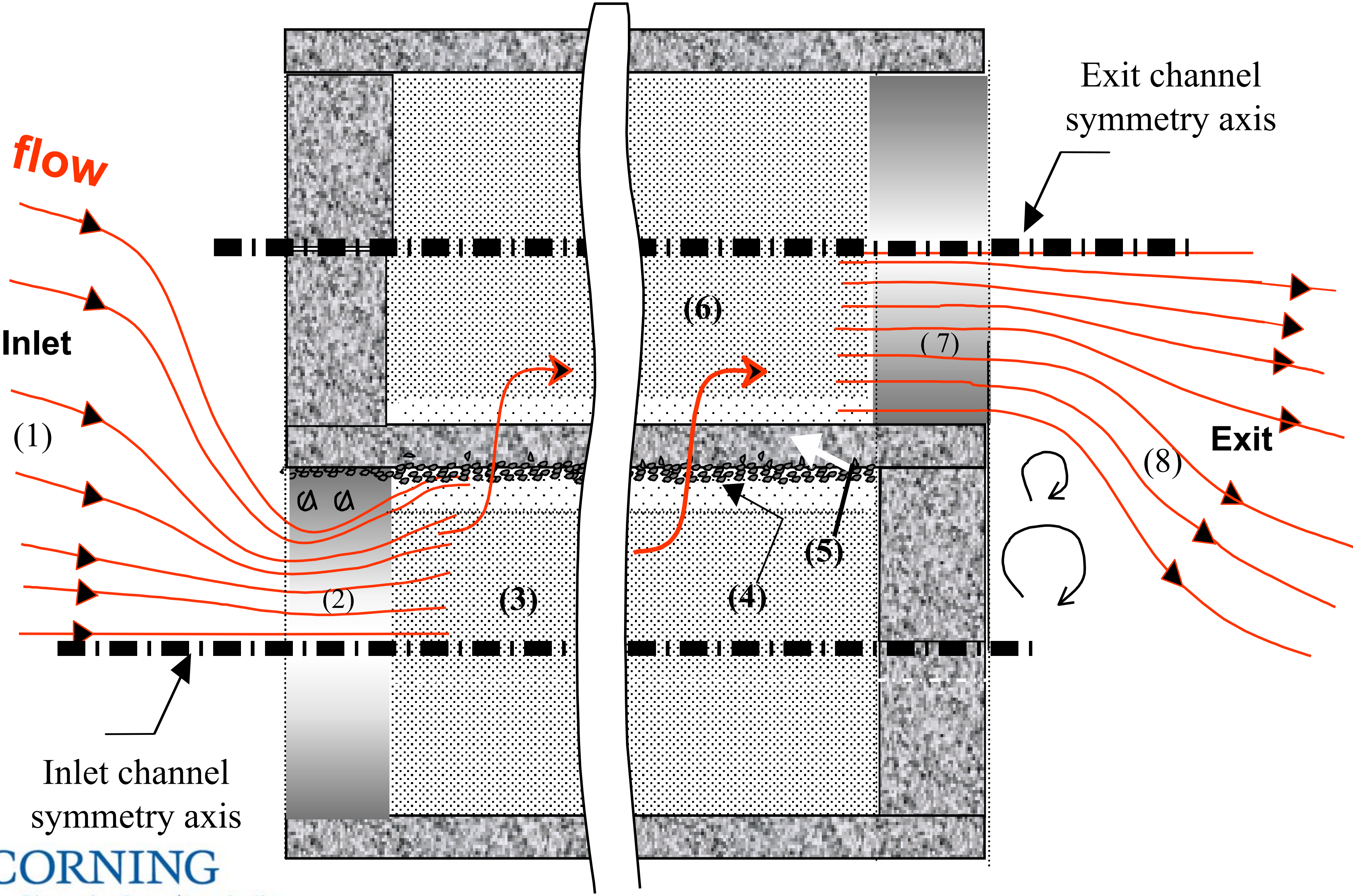


CORNING

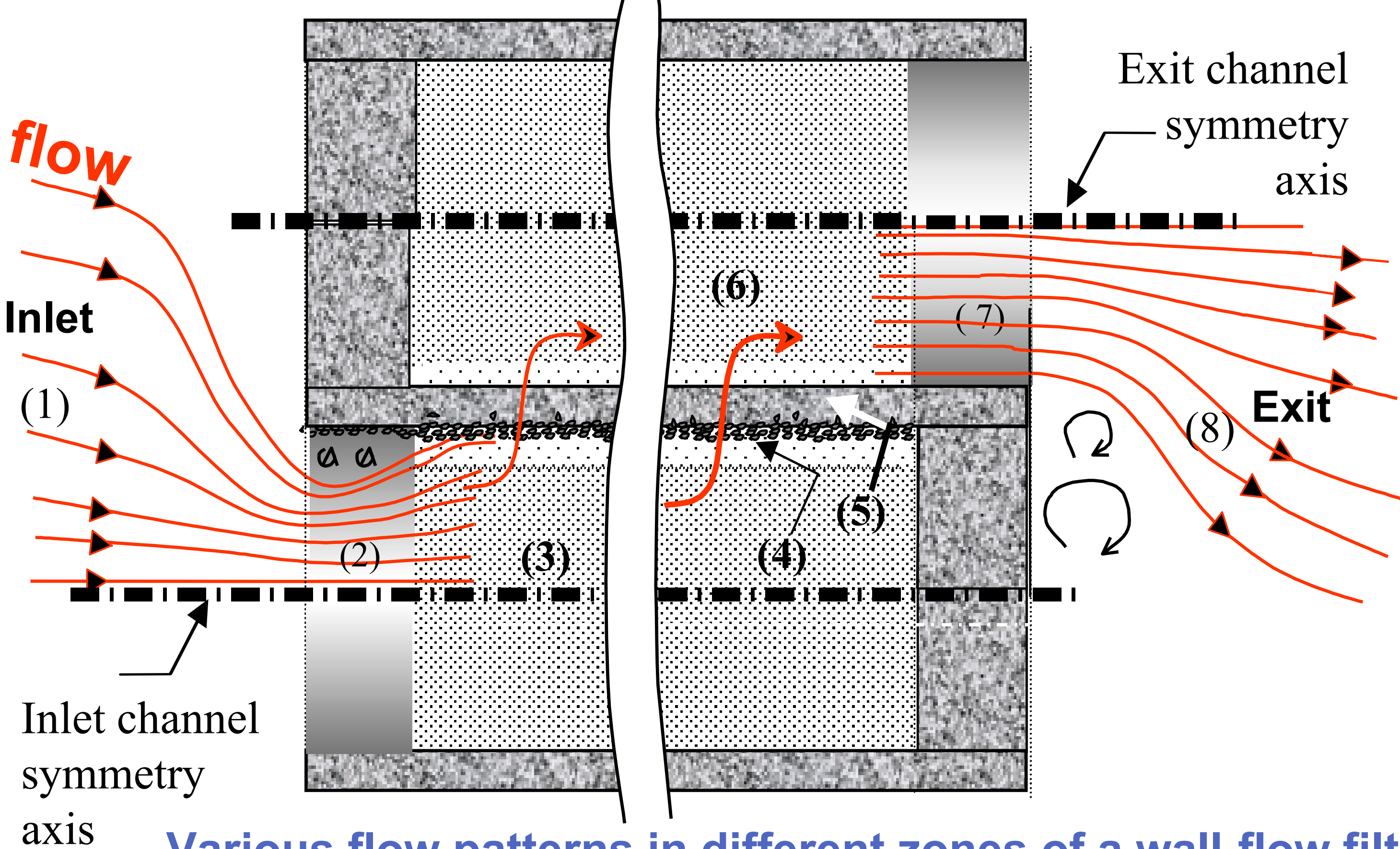


CORNING
Discovering Beyond Imagination

Various Flow Regimes In a Wall-Flow Filter



CORNING
Discovering Beyond Imagination



Various flow patterns in different zones of a wall-flow filter:

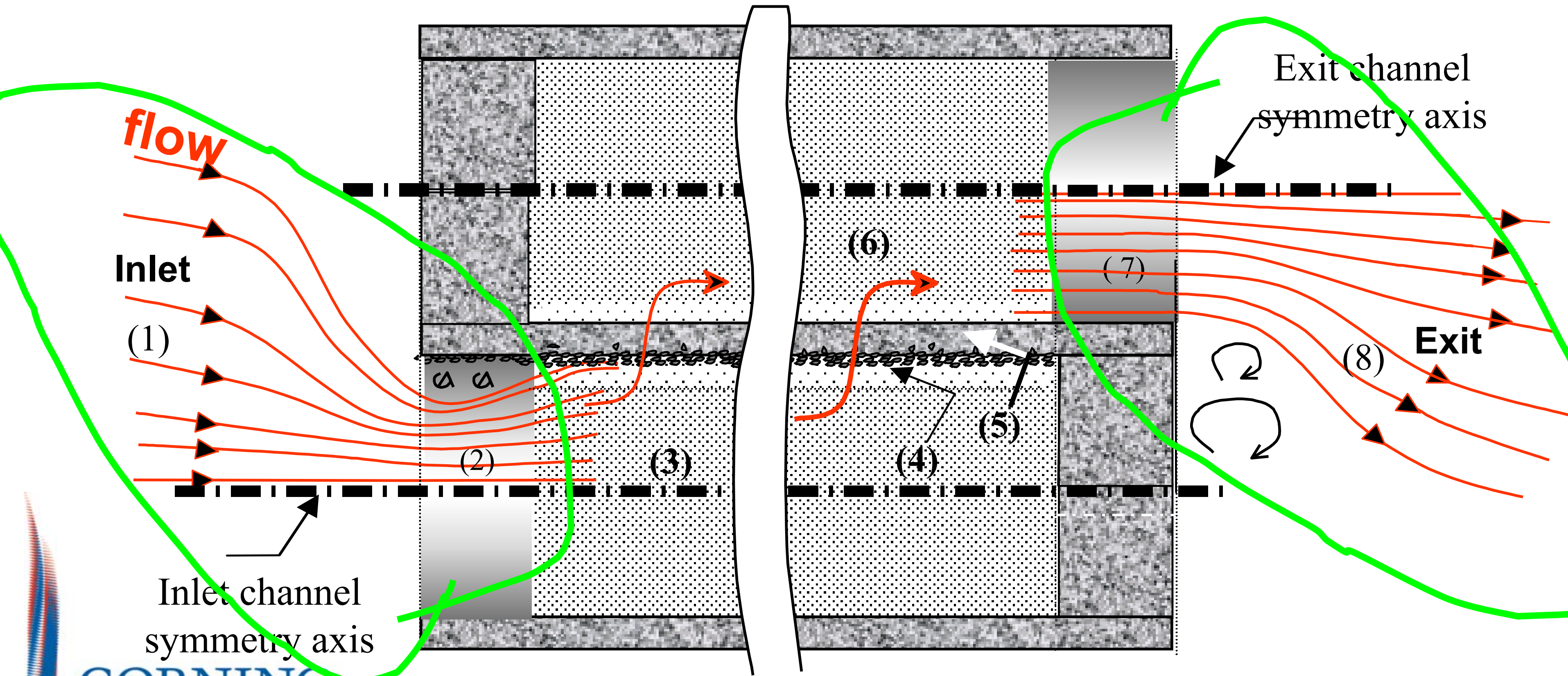
Flow in zone 1: free-shear flow, dominated by local contraction.
In 2 (shaded area): developing boundary layer dominated by wall-friction.
In 3 (densely dotted area): mostly axial (1-d) dominated by wall-friction.
In 4 (lightly dotted area): Darcy flow through the particulate layer.
In 5: Darcy flow through the porous wall.
In 6: same as 3.
In 7: similar to 2.
In 8: flow deceleration; hydrodynamic separation forming eddy pairs and local mixing.

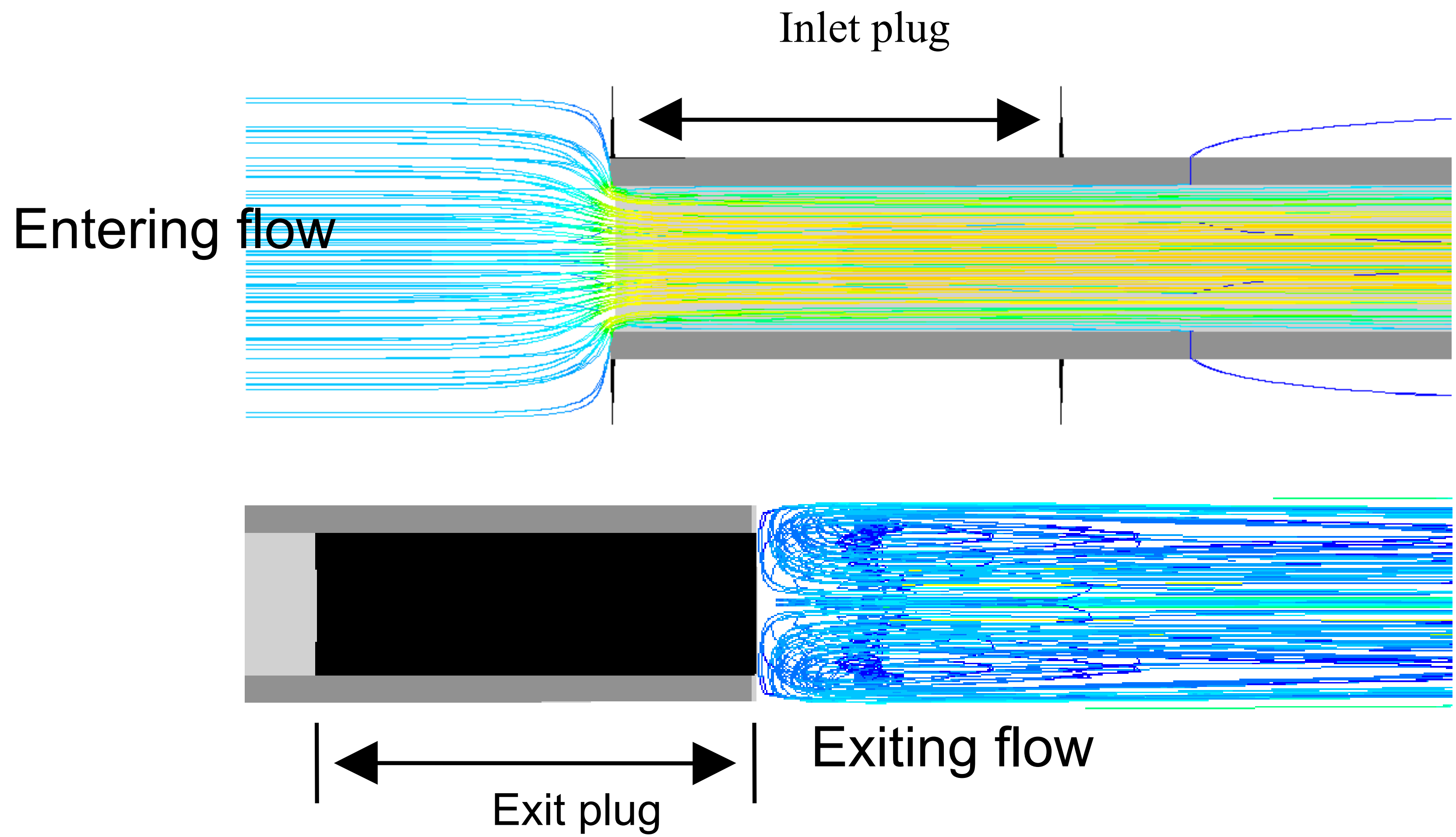
CORNING
Discovering Beyond Ima

Pressure drop contributions:

- **Inlet / exit effects**

$$\Delta P = \frac{\rho \quad \bar{u}^2_{entrance}}{2}\left[\zeta\left(\frac{L}{\alpha}\right)^2\right] \longrightarrow \Delta P = \frac{\rho Q^2(\alpha + w_s)^4}{V^2_{trap}\alpha^2}\left[2\zeta\left(\frac{L}{\alpha}\right)^2\right]$$





- **Inlet flow: smooth streamlines; stable.**
- **Exit flow: separation; eddy pairs.**
- **Exit effect contribution to PD ≅ twice inlet effect contribution***

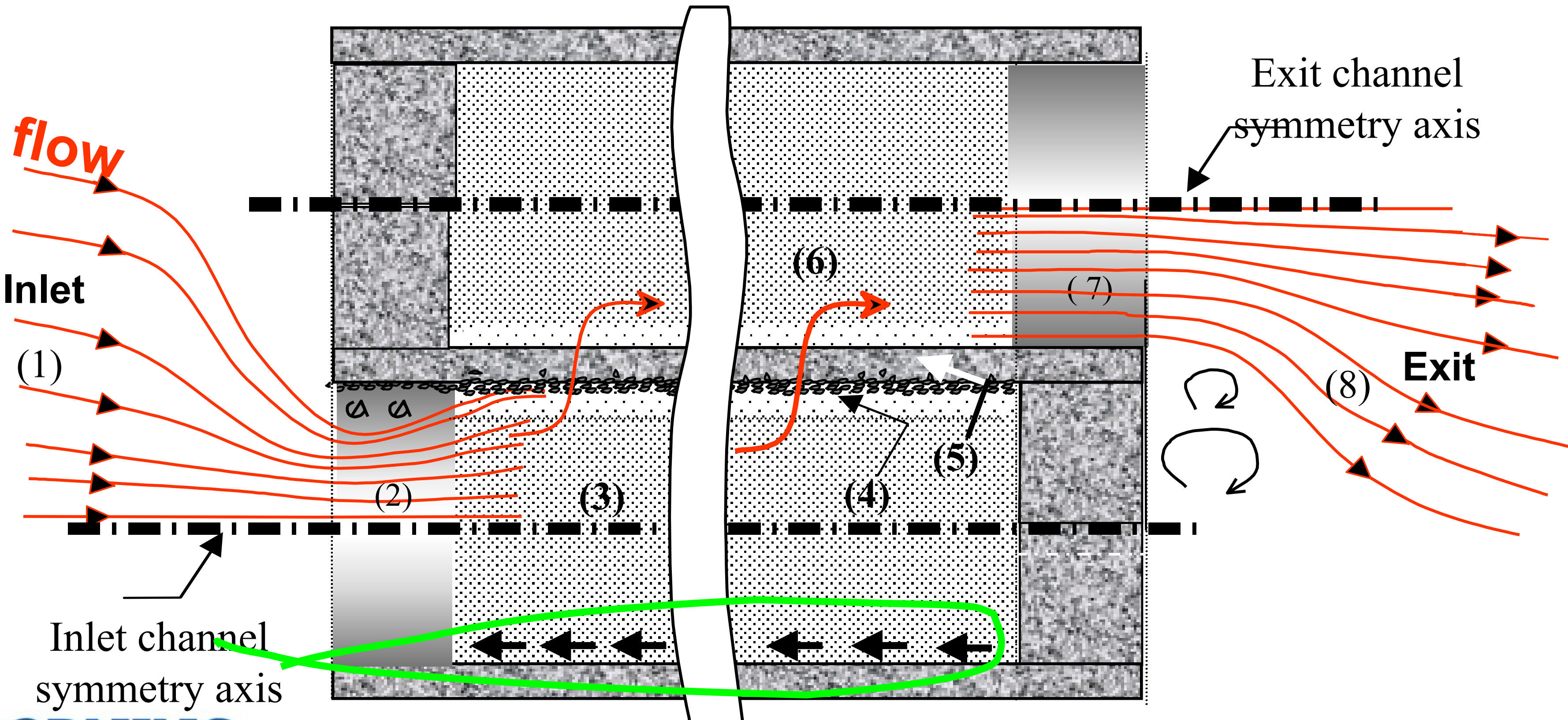
CORNING
Discovering Beyond Imagination

SAE-2001-01-0909

Pressure drop contributions:

• **channel flow friction with the walls**

$$\Delta P = \frac{\mu L}{2\alpha^2}\,\overline{u}_{channel} \longrightarrow \Delta P = \frac{\mu Q}{2V_{trap}}(\alpha + w_s)^2\left[\frac{4FL^2}{3}\left(\frac{1}{(\alpha - 2w)^4} + \frac{1}{\alpha^4}\right)\right]$$

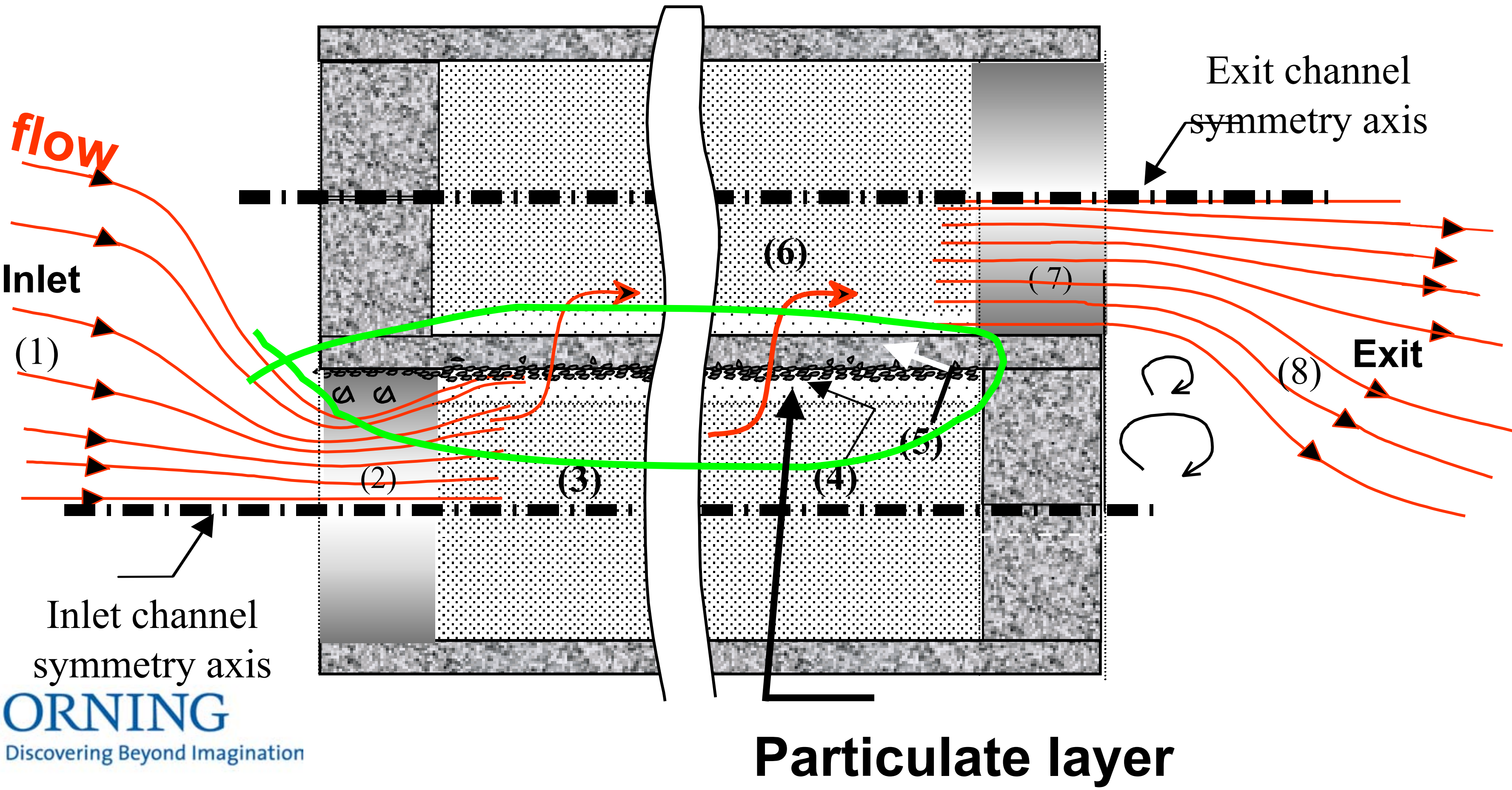


CORNING
Discovering Beyond Imagination

Pressure drop contributions:

- **Flow through the particulate layer -- Darcy effect**

$$\Delta P = \frac{\mu \, w_{soot}}{k_{soot}} \, \bar{u}_{wall} \longrightarrow \Delta P = \frac{\mu Q}{2V_{trap}} (\alpha + w_s)^2 \left[\frac{1}{2k_{soot}} \ln\left(\frac{\alpha}{\alpha - 2w_{soot}} \right) \right]$$

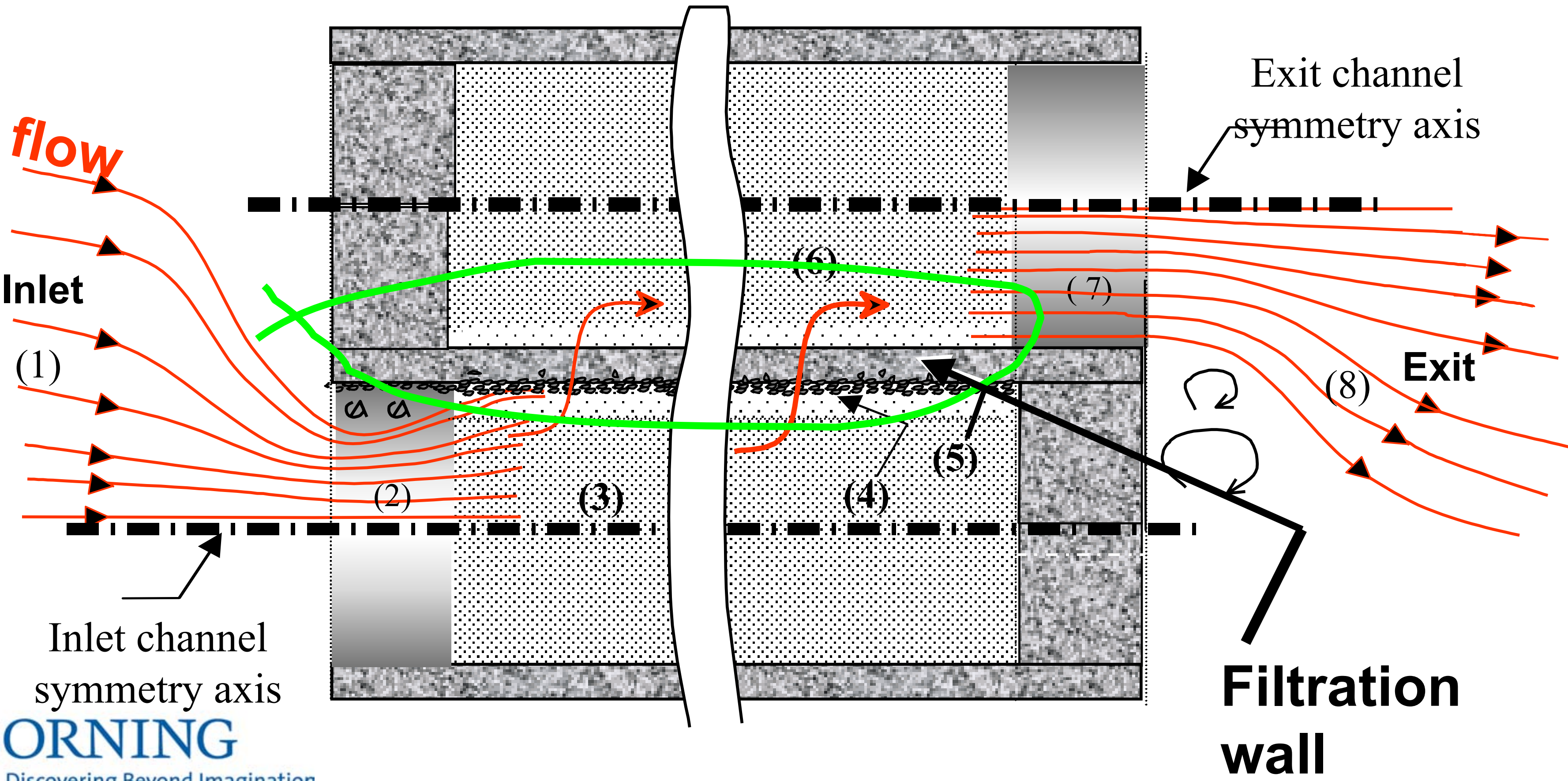


CORNING
Discovering Beyond Imagination

Pressure drop contributions:

- **Flow through the filtration wall -- Darcy effect**

$$\Delta P = \frac{\mu\, w_s}{k_s}\, \bar{u}_{wall} \longrightarrow \Delta P = \frac{\mu Q}{2V_{trap}}(\alpha + w_s)^2 \left(\frac{w_s}{k_w \alpha} \right)$$

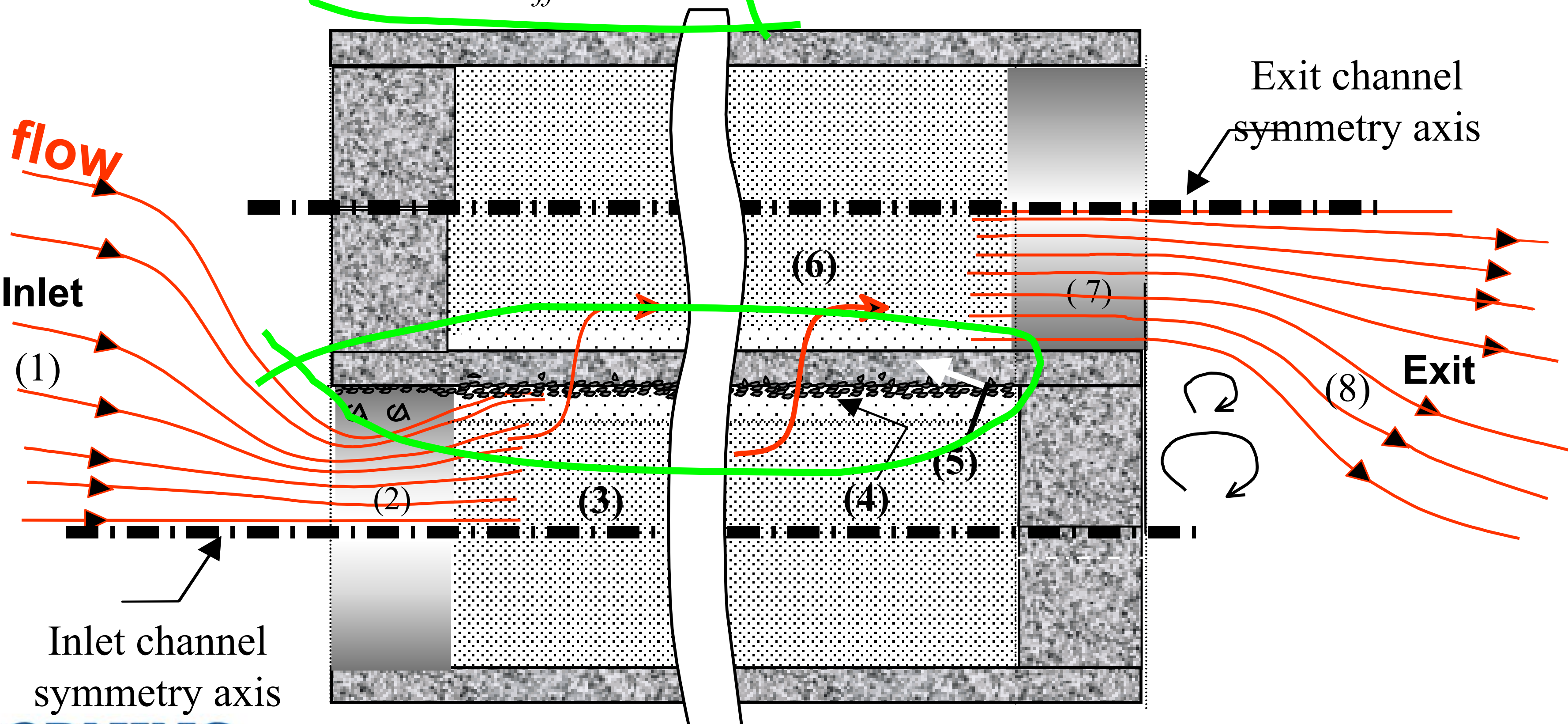


CORNING
Discovering Beyond Imagination

Pressure drop contributions:

- **Flow through the filtration wall -- Forchheimer effect**

$$\Delta P = \frac{\mu\, w_s}{k_s}\,\bar{u}_{wall} + \underbrace{\beta\,\rho\, w_s\,\bar{u}_{wall}^{\;2}}_{Forchheimer\ effect} \rightarrow \Delta P = \frac{\rho Q^2 (\alpha + w_s)^4}{V_{trap}^2 \alpha^2}\left[\frac{\beta w_s}{4}\right]$$



CORNING
Discovering Beyond Imagination

Total filter pressure drop = summation of all individual components

$$\Delta P = \frac{\mu Q}{2V_{trap}}(\alpha + w_s)^2\left[\frac{w_s}{k_w \alpha} + \frac{1}{2k_{soot}}\ln\left(\frac{\alpha}{\alpha - 2w_{soot}}\right) + \right.$$

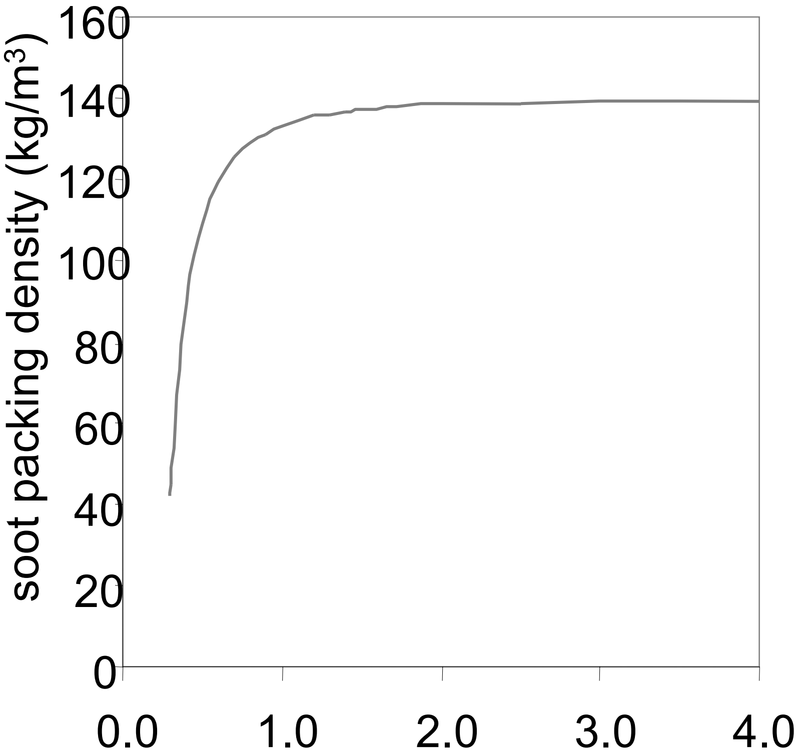
$$\left. + \frac{4\mathrm{FL}^2}{3}\left(\frac{1}{(\alpha - 2w_{soot})^4} + \frac{1}{\alpha^4}\right)\right] +$$

$$+ \frac{\rho Q^2 (\alpha + w_s)^4}{V_{trap}^2 \alpha^2}\left[\frac{\beta w_s}{4} + 2\zeta\left(\frac{L_{plug}}{\alpha}\right)^2\right]$$

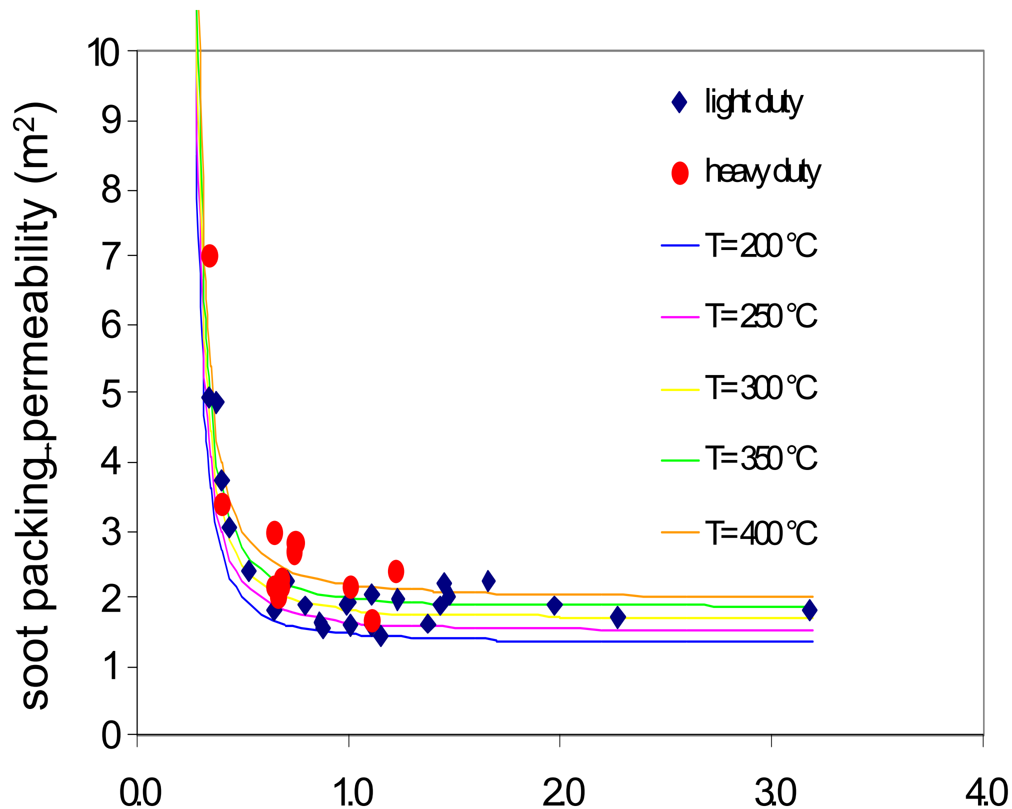
with $$w_{soot} = \frac{\alpha - \sqrt{\alpha^2 - \dfrac{m_{soot}}{n_{open} L \rho_{soot}}}}{2}$$

CORNING
Discovering Beyond Imagination

Understanding "soot cake layer properties" are essential for accurate predictions of DPF pressure drop.



Peclet number of mass transport



Peclet number of mass transport

$$Pc = U_w \ d_c / D_p$$

(SAE-2002-FL-83, *in review*.)

CORNING

Experiments to verify the pressure drop model

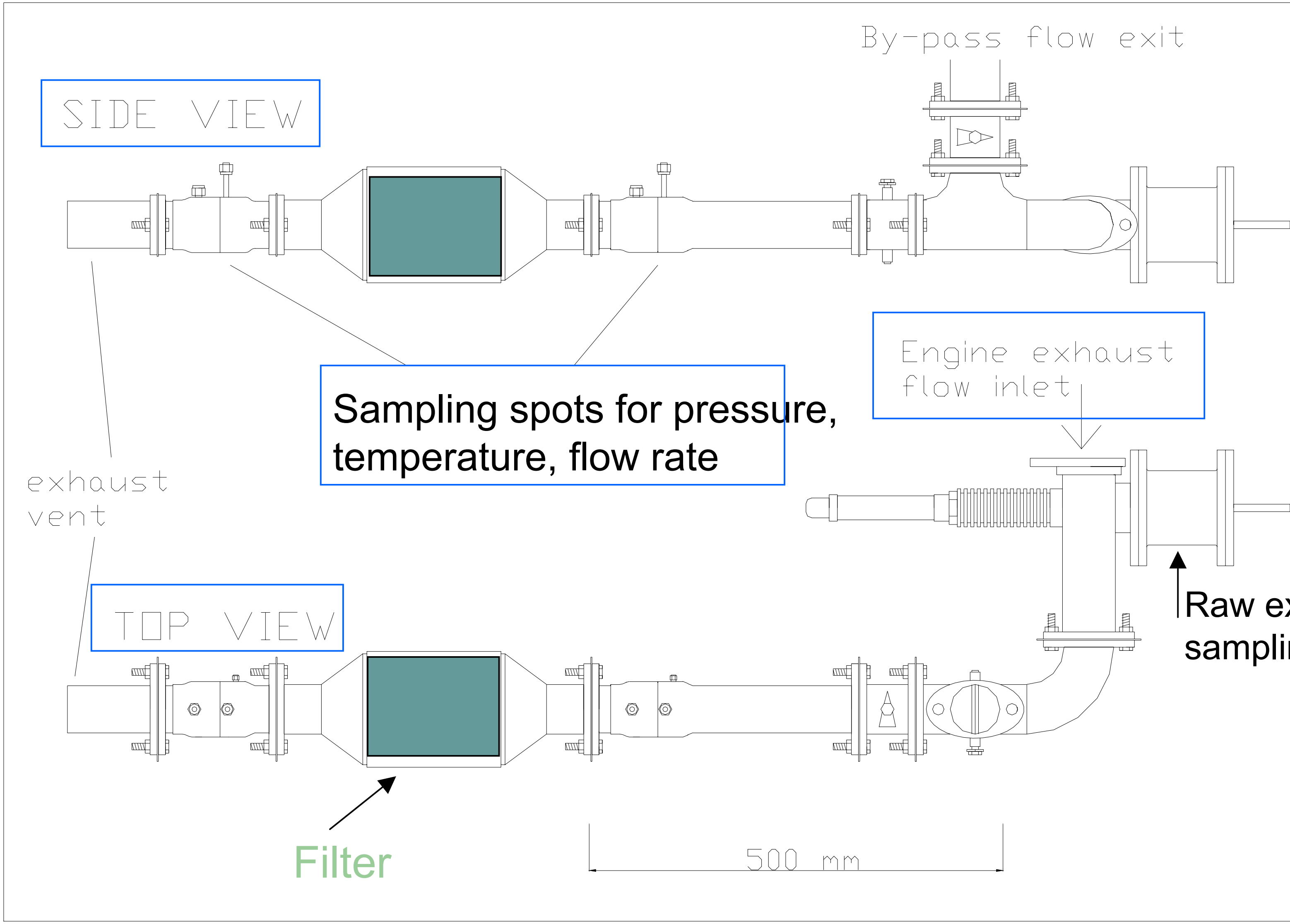
Parameter	Min-Max. value	Unit
Filter size (diam.xlength)	4.66x6 – 12x15	in x in
Filter cell density	100 – 200	cpsi
Filter wall thickness	12- 17	mil
Filter geometry	Round, Oval	-
Engine flow rate	97.5 – 790	kg/hr
Engine flow temperature	240 – 370	° C
Particulate emission rate	1.45 – 20.8	gr/hr
Loading duration	1.3 – 118	hr

Range of parameters:

- Filtration characteristics of filters changing by 20 fold.
- Flow rate range changing by nearly an order of magnitude.
- Both light duty and heavy duty Diesel engines utilized.
- Particulate emission rate changing by more than an order-of-magnitude.
- Duration of filter loading changing by two order-of-magnitudes.
- 41 filter loading tests on Diesel engine platforms.

CORNING

Experiments (cont.)



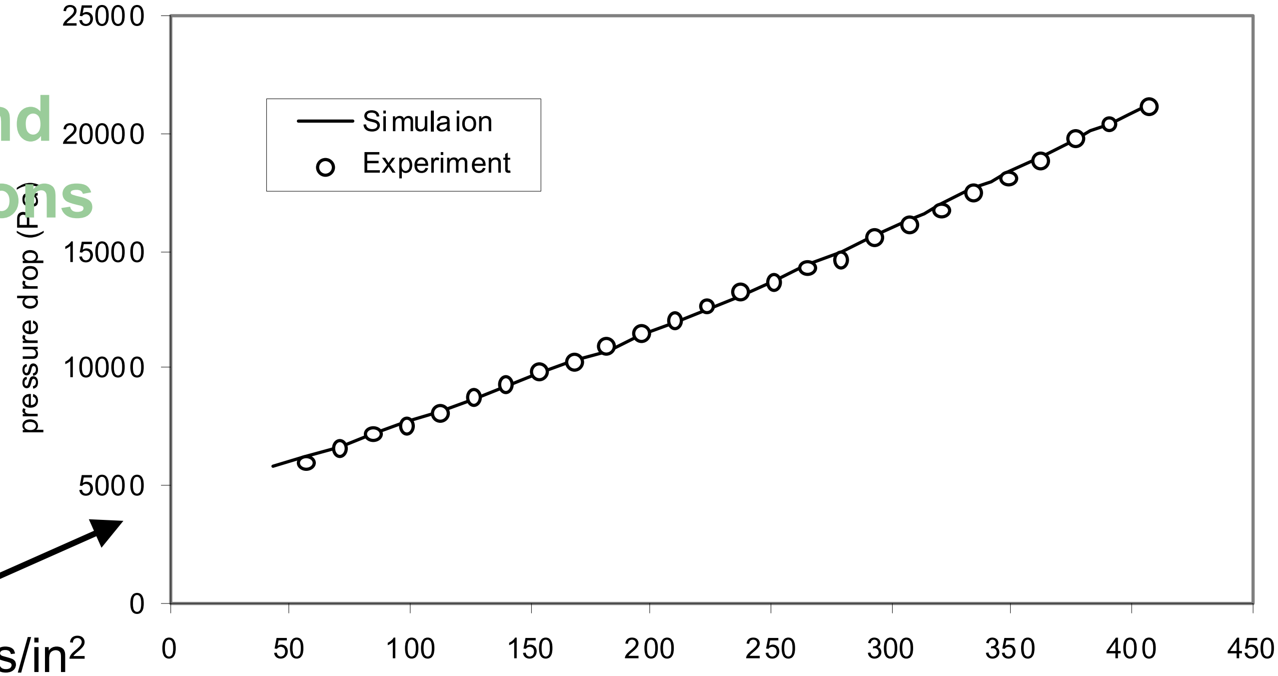
Test bench setup for filter soot-loading (engine not shown).

CORNING

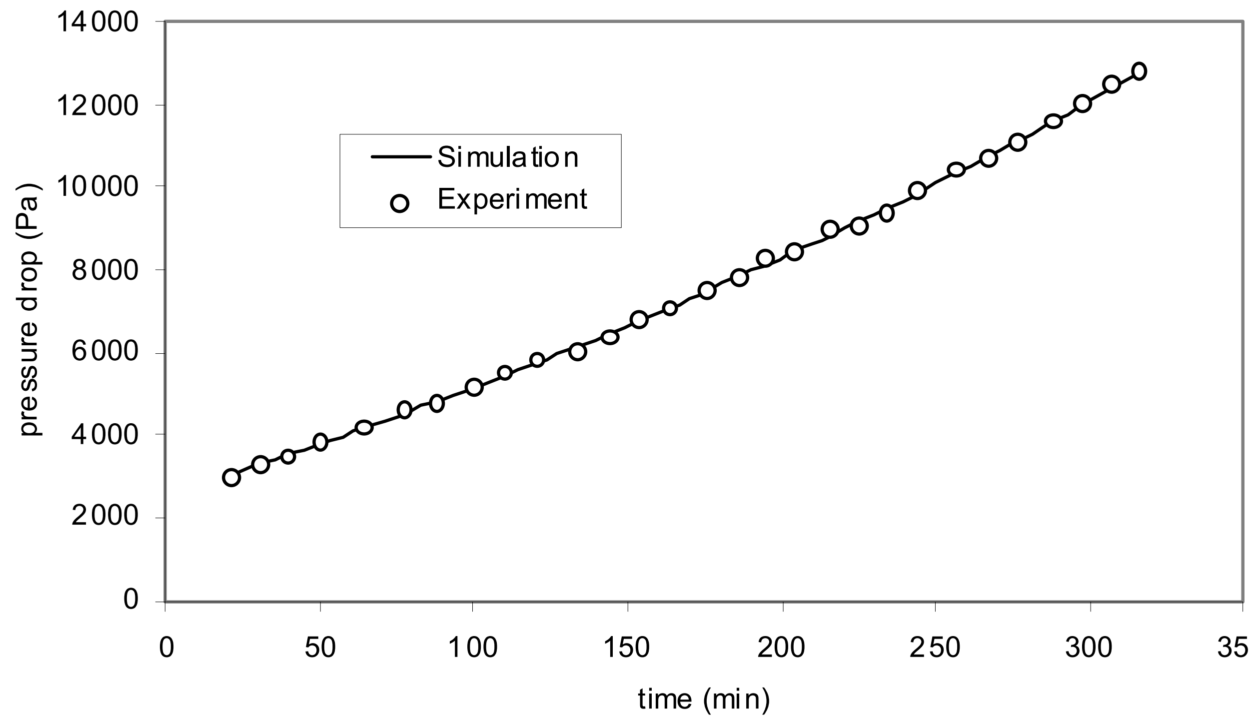
IV. Comparing experiments and model predictions

(A) **Small** filters on **light duty** Diesel engine.

Filter Size: 4.66 " x 6 "
filter cell density: 100 cells/in^2
Wall thickness: 17 mil.
Engine: light duty.



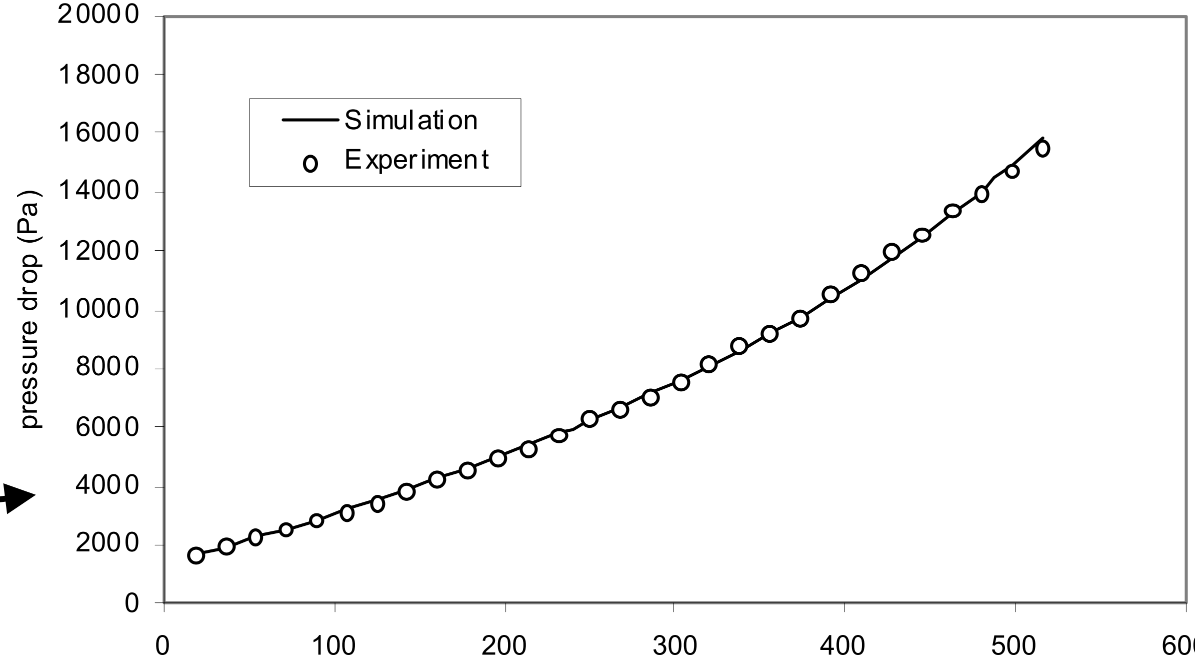
Filter size: 4.66 " x 6 "
Filter cell density: 200 cells/in^2
Wall thickness: 12 mil.
Engine: light duty.



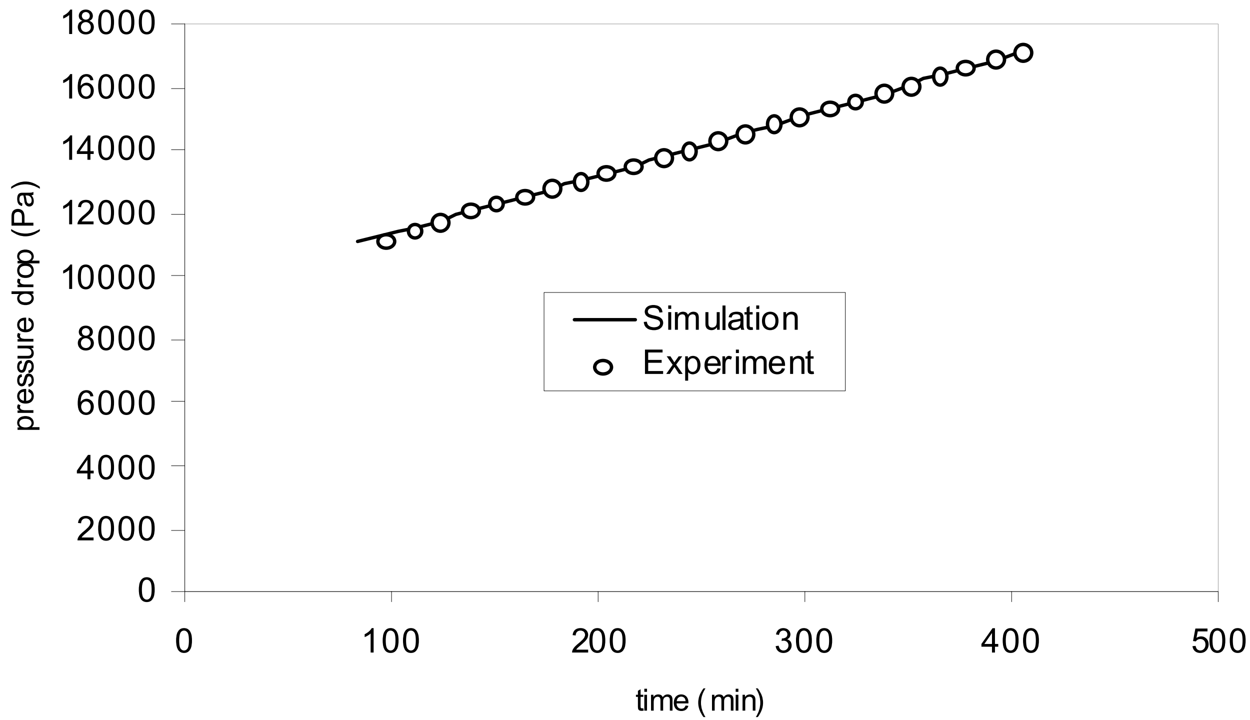
Comparison (cont.)

(B) **Medium** size filters on **light** and **heavy duty** Diesel engines.

Filter size: 7.5 " x 8 "
Filter cell density: 100 cells/in^2
filter wall thickness: 17 mil.
Engine: light duty.



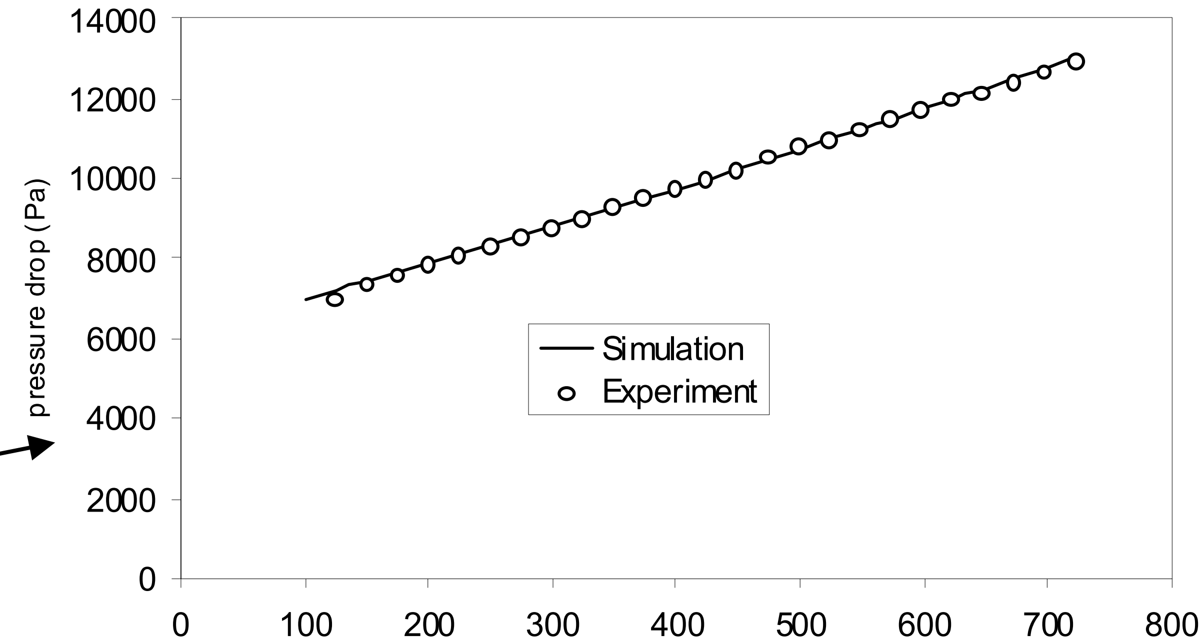
Filter size: 7.8 " x 12 "
Filter cell density: 100 cells/in^2
Filter wall thickness: 17 mil.
Engine: heavy duty.



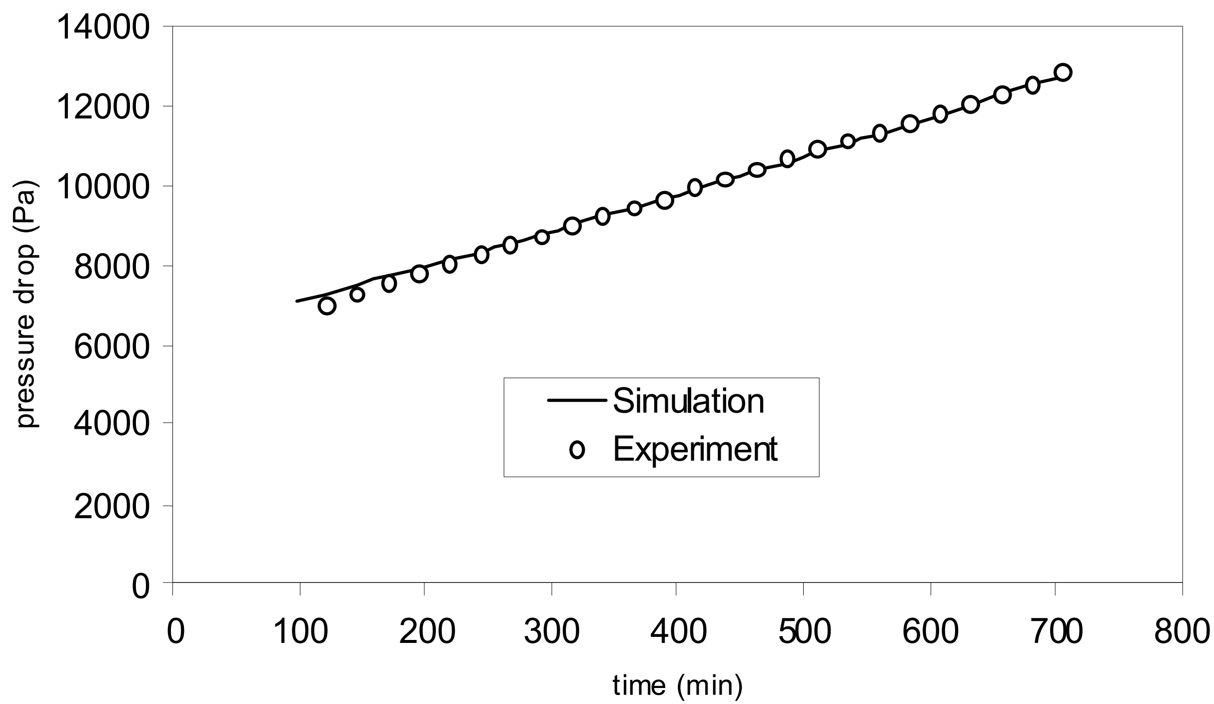
Comparison (cont.)

(C) **Large** filters on **heavy duty** Diesel engines.

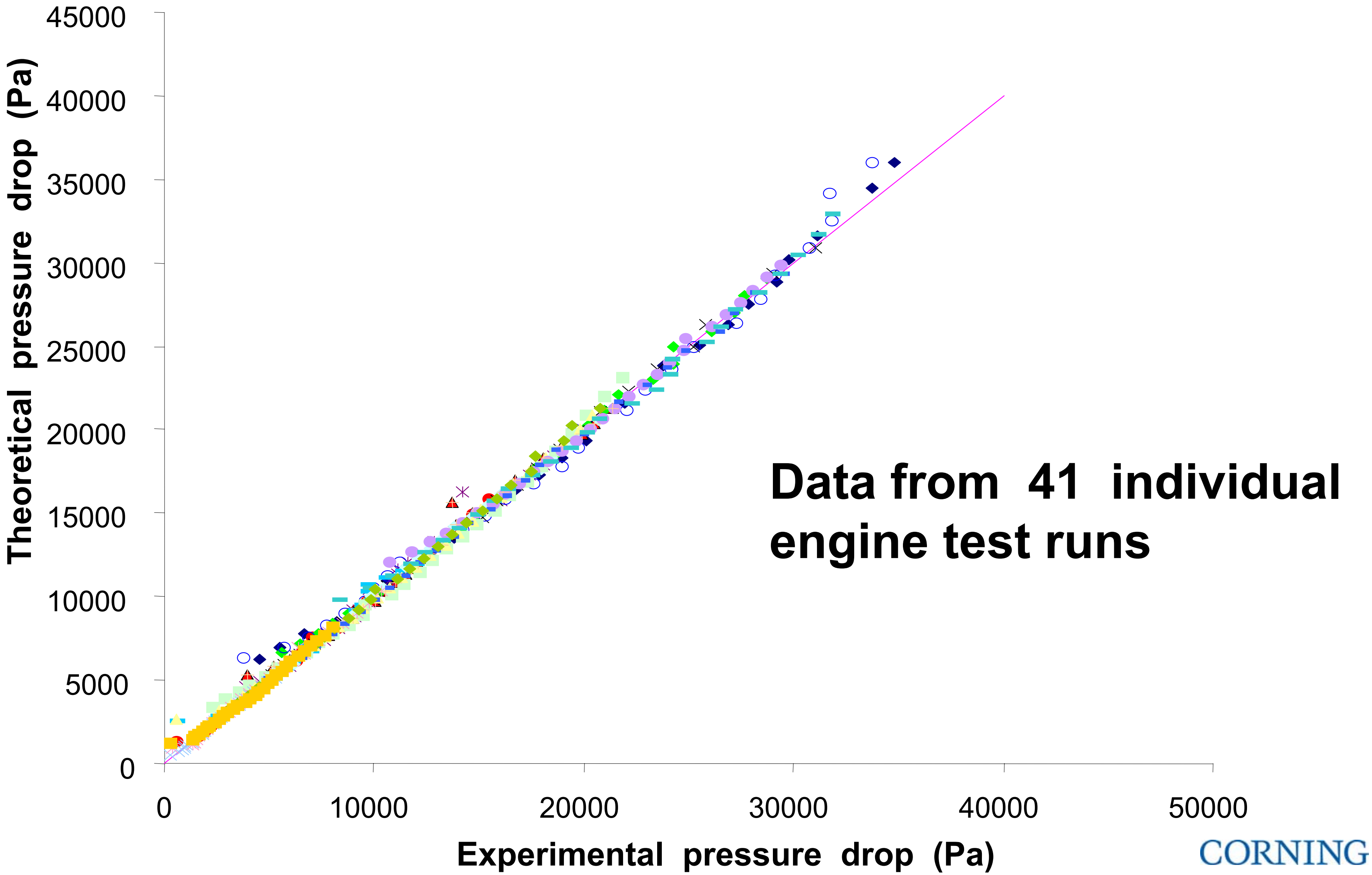
Filter size: 11.25 " x 12 "
Cell density: 100 cells/in^2
Wall thickness: 17 mil.
Engine: <u>heavy duty</u>.



Filter size: 12 " x 15 "
Cell density: 100 cells/in^2
Wall thickness: 17 mil.
Engine: <u>heavy duty</u>.



Comparison between all the test data collected and model prediction



CORNING

Conclusions

- Reasonable model for DPF pressure drop (cake filter mode) available.
- Model can be customized to catalyzed filters.
- Model available for DPF deep-bed deposit mode*.
- What is not available / needed:
    - ***Ash*** -- effect of ash on filter pressure drop: ash "creation", "transport", "deposit", and "sintering" in filter channels and walls.
    - ***Particulate deposit:*** modes of uniform and non-uniform soot deposits, axially and radially.
    - ....

CORNING
Discovering Beyond Imagination

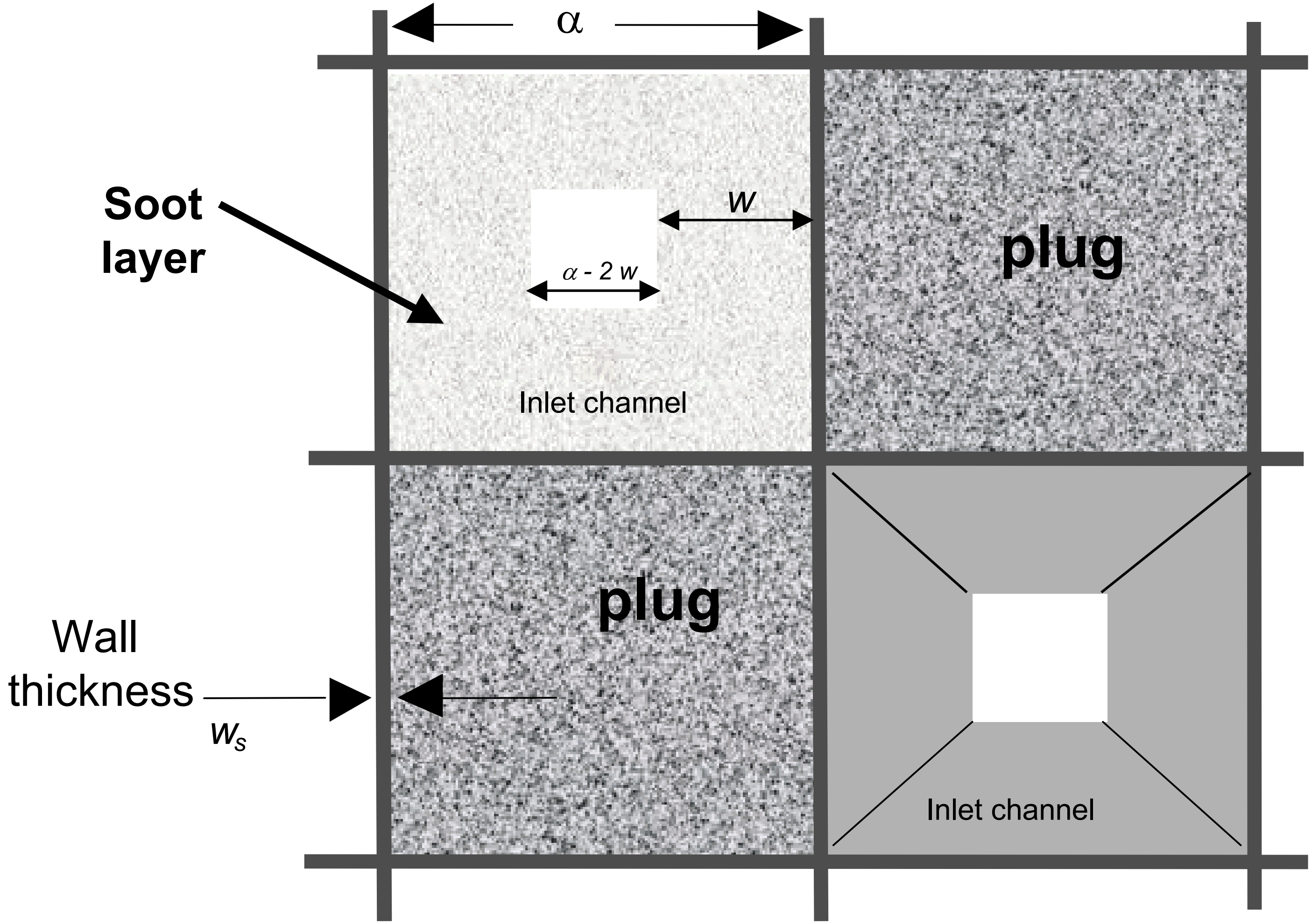
* SAE - 2001 - 1016

Acknowledgment: Contributions of Dr. Konstandopoulos and his research team (CERTH/CPERI) to our understanding of the theory and practice of trap pressure drop is hereby acknowledged.

CORNING

Appendix:

1. Geometry



2. Nomenclature

d_c	Primary soot particle size	α	Filter cell opening (hydraulic diameter)
D_p	Diffusion Coeff.	β	Forchheimer coefficient for porous wall
F	Factor equal to 28.454.	ΔP	Pressure drop across the filter
k_w	Filter wall permeability	ζ	Contraction/expansion inertial losses coefficient
k_{soot}	Particulate layer permeability	μ	Exhaust gas dynamic viscosity
L	Effective filter channel length	ρ	Exhaust gas density
$\dot{m}$	Exhaust gas mass flow rate	ρ_{soot}	Particulate packing density in cake deposit
m_{soot}	Particulate mass in the deposited layer	σ	Filter cell density
Q	exhaust volumetric flow rate		
u_{ch}	Flow speed in filter channel in the axial direction		
u_w	Flow speed in filter channel toward the filter wall (wall-flow speed)		
V_{trap}	Trap volume		
w_{soot}	Thickness of the particulate cake layer		
w_s	Thickness of the porous membrane (filter wall)		

CORNING

Discovering Beyond Imagination