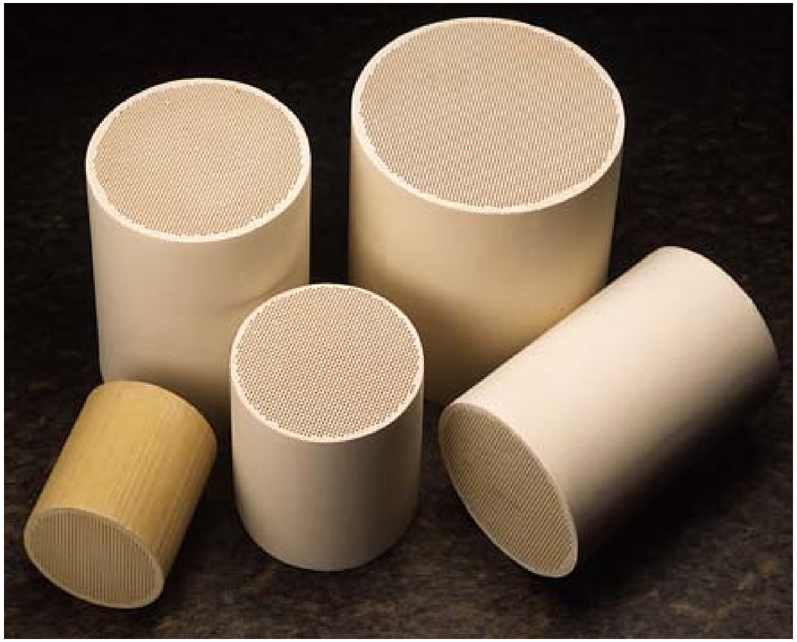
Modeling Pressure Drop of Wall-Flow Diesel Particulate Filters

Part 1: Early Development -- Model for Clean Filters



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October 2001, Detroit, MI

CLEERS NOx Trap / DPF Modeling Workshop

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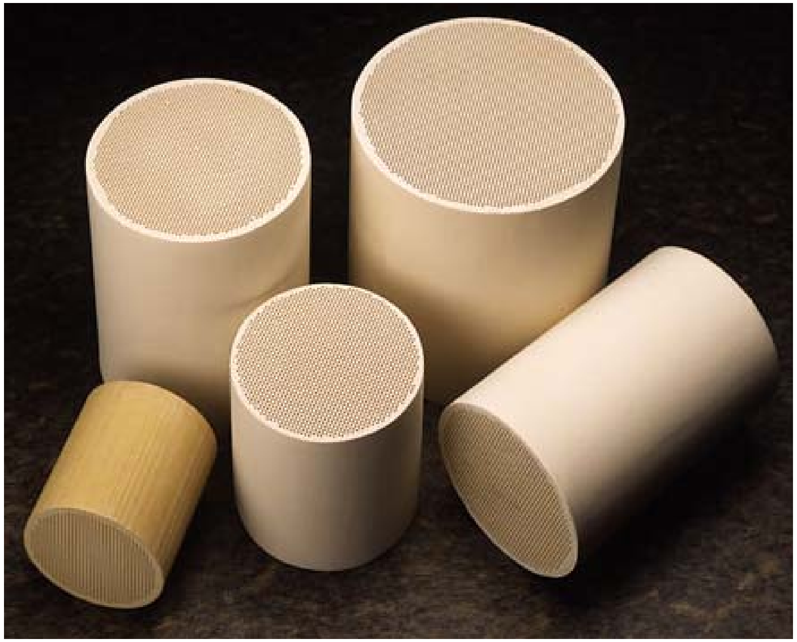
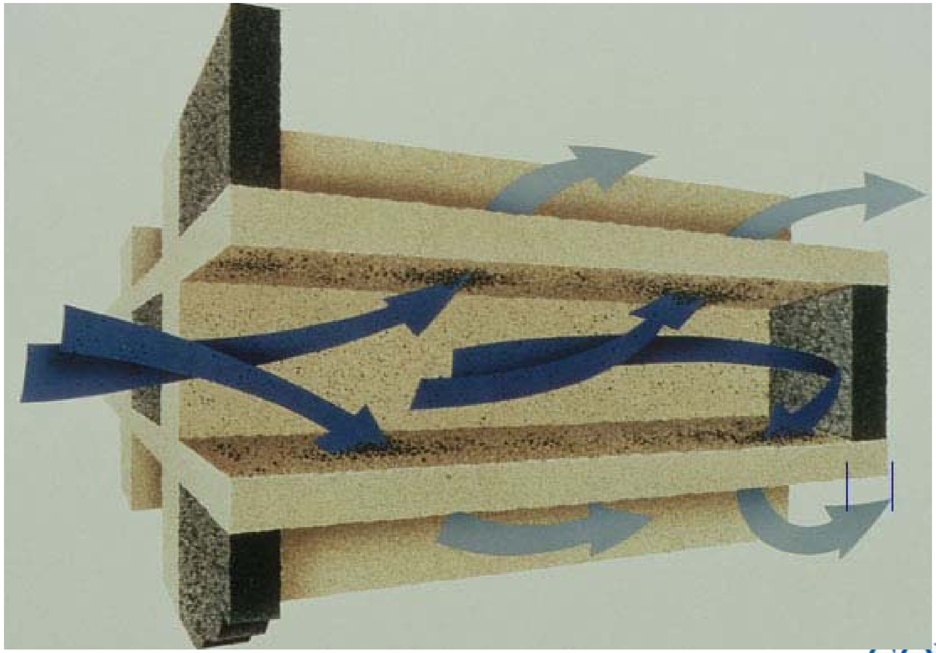
Discovering Beyond Imagination

A DPF is composed of many individual cells alternately plugged.



Incoming flow enters the open cells and penetrates through the porous walls into neighboring cells.



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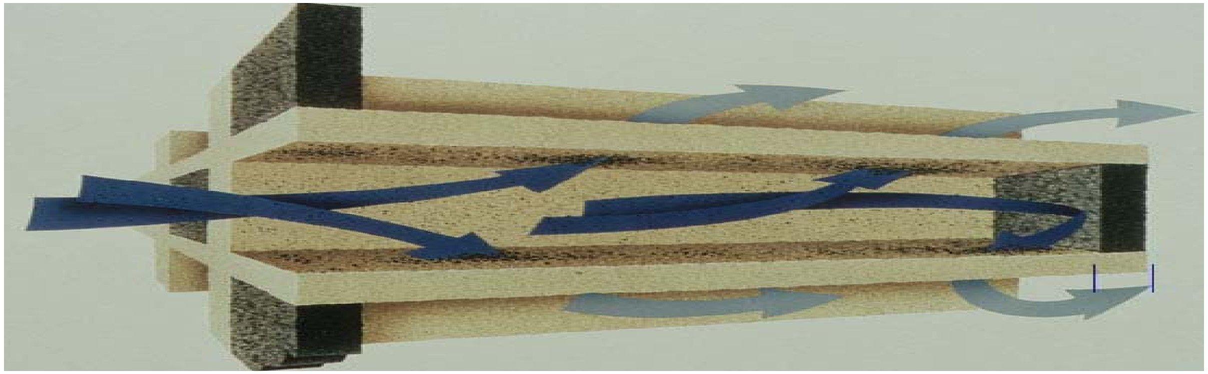
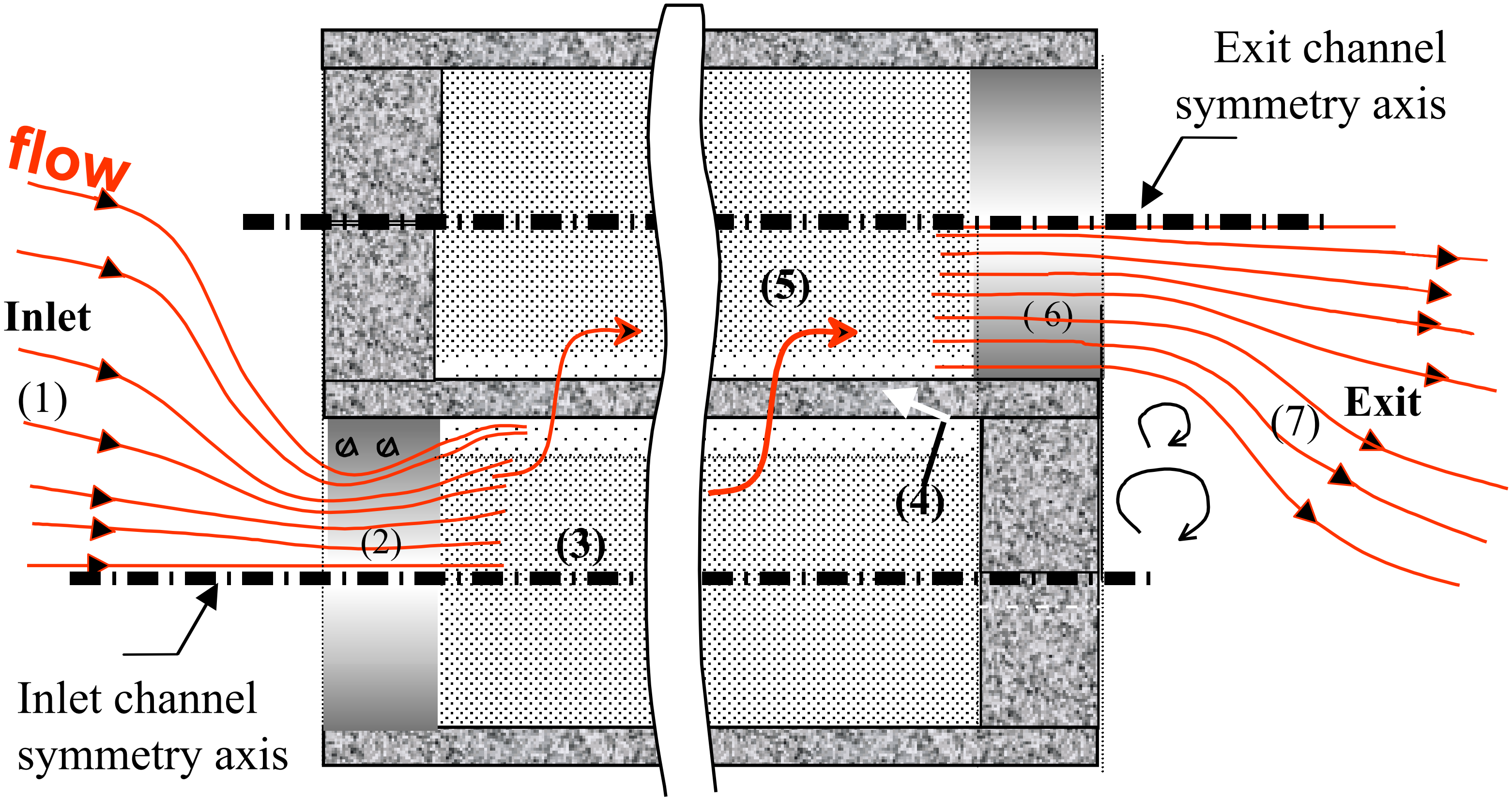
Flow into a single cell:





Flow through a clean DPF cell travels through 7 different zones.
Experiences 5 different ‘flow regimes’ (Darcy flow / frictional / inlet & exit / Forchheimer losses).

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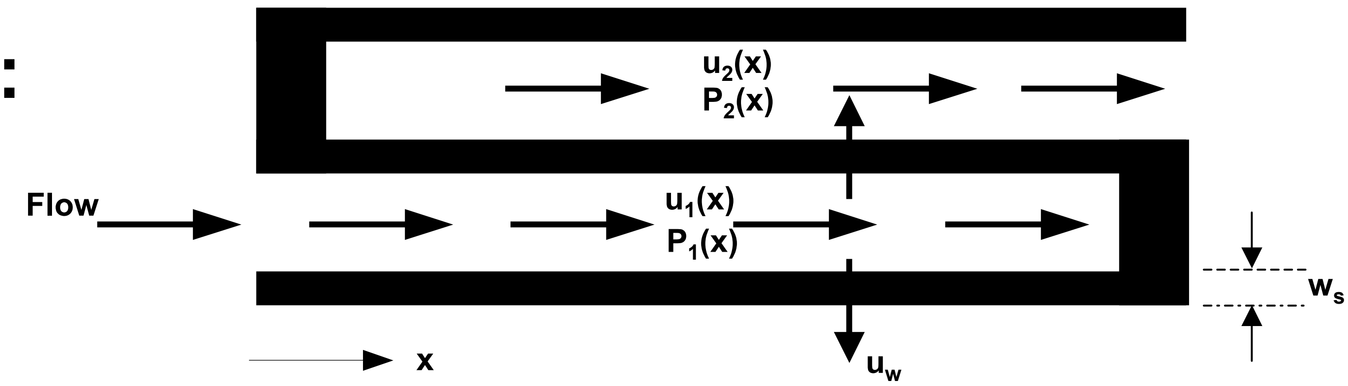
Formulation of Pressure Drop: Clean Filters



Mass Balance

$$\textbf{Inlet Cell}: \frac{d}{dx}\left(\rho\, u_1\right) = -\frac{4}{\mathbf{a}}\ \rho\, u_w$$

$$\textbf{Outlet Cell}: \frac{d}{dx}\left(\rho\, u_2\right) = \frac{4}{\mathbf{a}}\ \rho\, u_w$$

Momentum Balance

$$\textbf{Inlet Cell}: \frac{d}{dx}\left(\rho\, u_1^2\right) = -\frac{\mathbf{dP_1}}{\mathbf{dx}} - \frac{\mathbf{S}}{\mathbf{A}}\tau_1$$

$$\textbf{Outlet Cell}: \frac{d}{dx}\left(\rho\, u_2^2\right) = -\frac{\mathbf{dP_2}}{\mathbf{dx}} - \frac{\mathbf{S}}{\mathbf{A}}\tau_2$$

Wall Pressure Drop

$$P_1 - P_2 = \frac{\mu}{k}\ u_w\ w_s$$

Boundary Conditions

$$u_1(o) = U$$
$$u_2(o) = 0$$
$$P_2(L) = P_{atm}$$

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The solution:

$$\Delta p_{filter} = \frac{\eta \cdot v_{channel,inlet\&exit} \cdot d_h \cdot w_{th}}{4 \cdot L_{filtration\ area} \cdot k} \cdot \left[A_1 + A_2 \cdot \left(\frac{1}{2} + \frac{c_1}{g_1} \cdot \left(e^{g_1} - 1\right) + \frac{c_2}{g_2} \cdot \left(e^{g_2} - 1\right) \right) + c_1 \cdot g_1 + c_2 \cdot g_2 \right]$$

$$A_1 = \frac{k}{d_h \cdot w_{th}} \cdot \frac{4 \cdot L_{filtration\ area}}{d_h} \cdot Re_{channel,\ inlet\&exit}$$

$$A_2 = 4 \cdot F \cdot \frac{k}{d_h \cdot w_{th}} \cdot \left(\frac{L_{filtration\ area}}{d_h} \right)^2$$

$$g_1 = A_1 - \sqrt{A_1^2 + 2 \cdot A_2} \qquad g_2 = A_1 + \sqrt{A_1^2 + 2 \cdot A_2}$$

$$c_1 = -\frac{1}{2} - c_2 \qquad c_2 = \frac{1}{2} \cdot \left[\frac{e^{g_1} + 1}{e^{g_2} - e^{g_1}} \right]$$

The model accounts for ΔP due to filtration wall and channel friction.

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Additional contributions:

- Friction between the flow and the channel plugs (viscous losses)

$$\Delta p_{plugs} = F \cdot \frac{\eta \cdot 2 \cdot L_{plug} \cdot v_{channel,inlet\&exit}}{d_h^2}$$

- Pressure drop due to the inlet and exit effects

$$\Delta p_{inlet\ \&\ exit} = \varsigma_{inlet\&exit} \cdot \frac{\rho}{2} \cdot v^2_{channel,inlet\&exit}$$

- **Sum up to yield total filter pressure drop:**

$$\boxed{\Delta \mathbf{P}_{\mathbf{total}} = \Delta \mathbf{P}_{\mathbf{filter}} + \Delta \mathbf{P}_{\mathbf{plugs}} + \Delta \mathbf{P}_{\mathbf{inlet\&exit}}}$$

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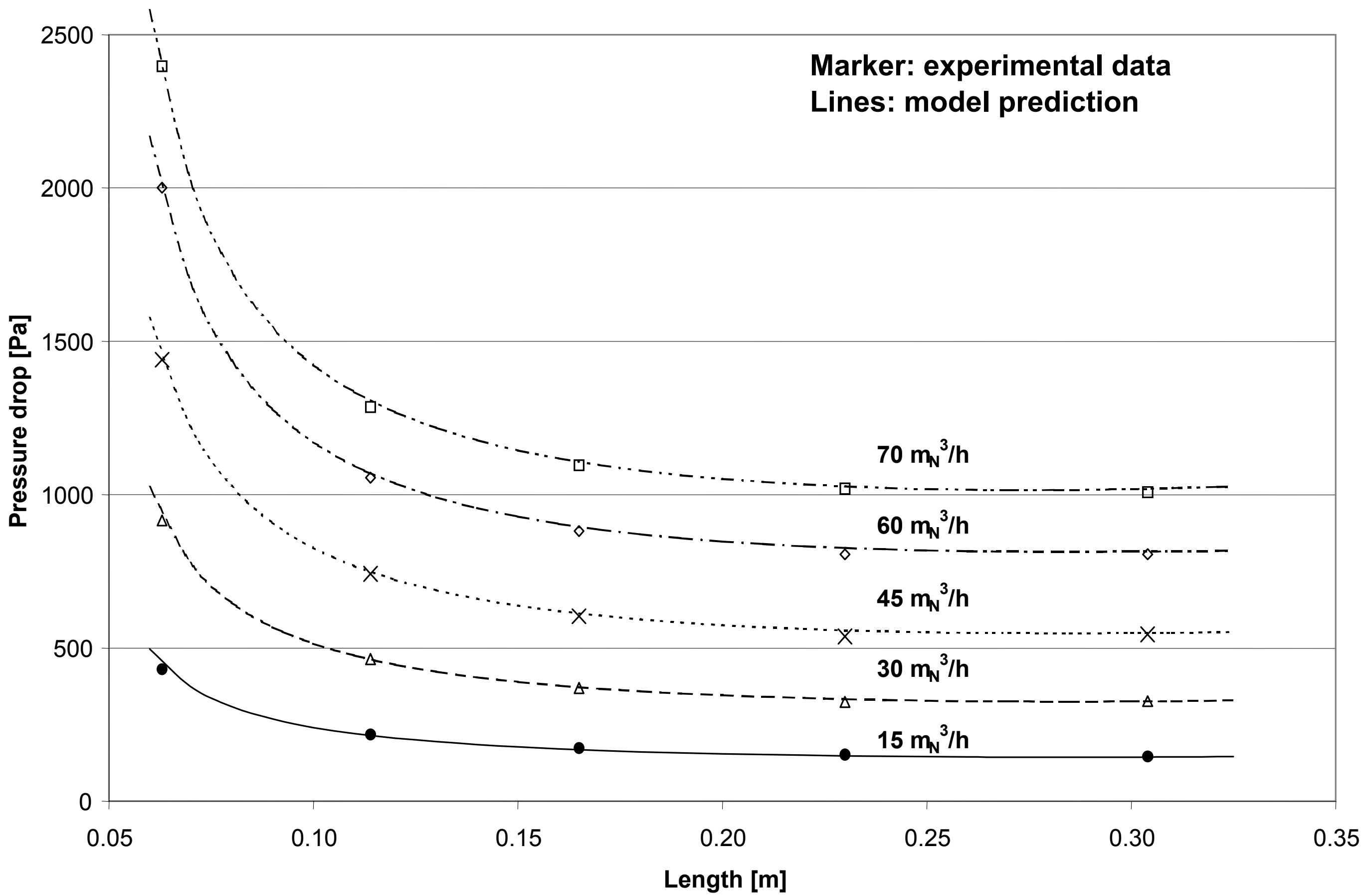
Comparison between Model and Experiment



Filters with cell density 100 cpsi

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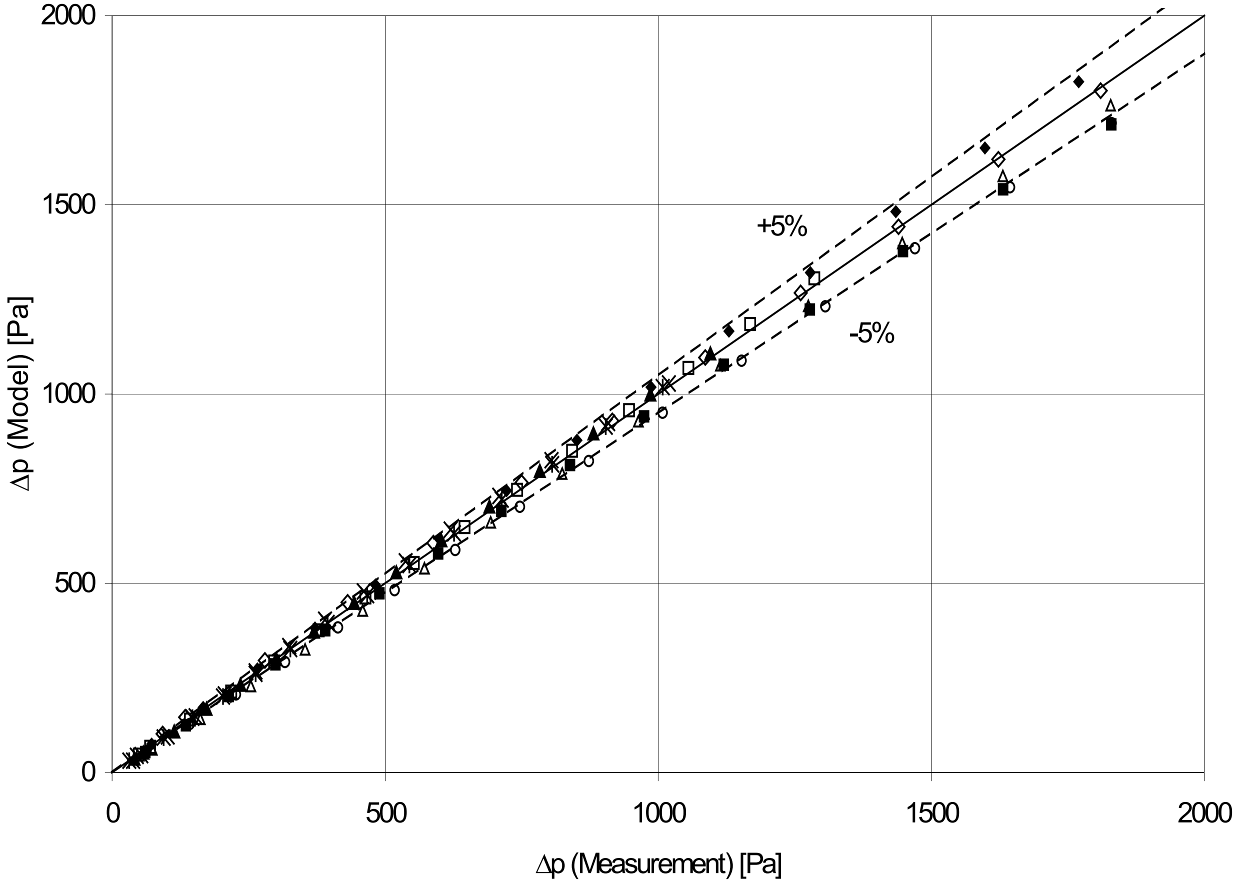
Overall Comparison between Model and Experiment



Overall Margin of Deviation: ± 5 %

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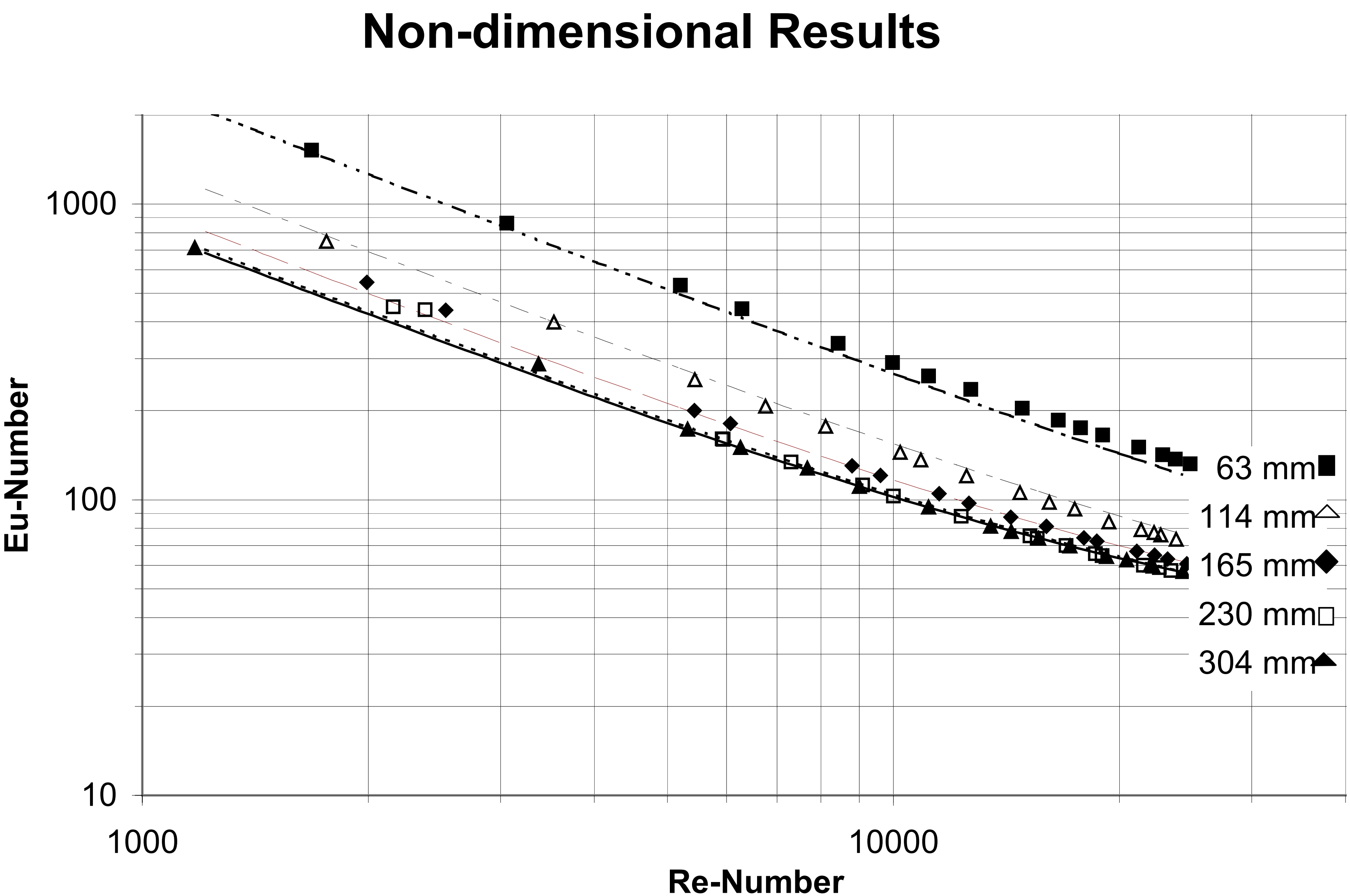
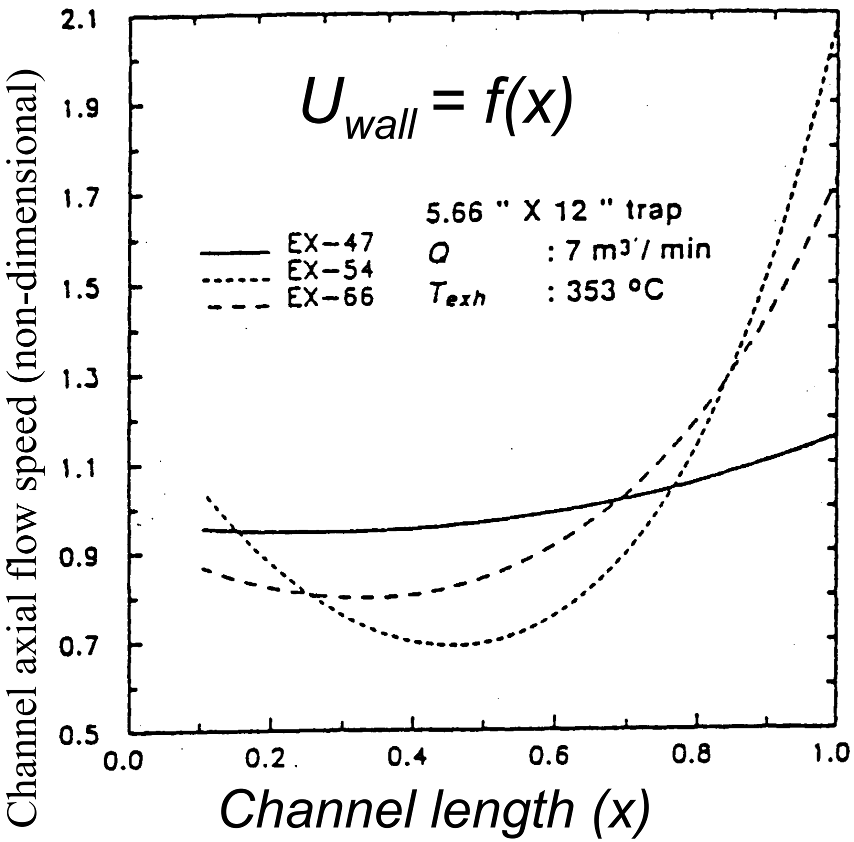
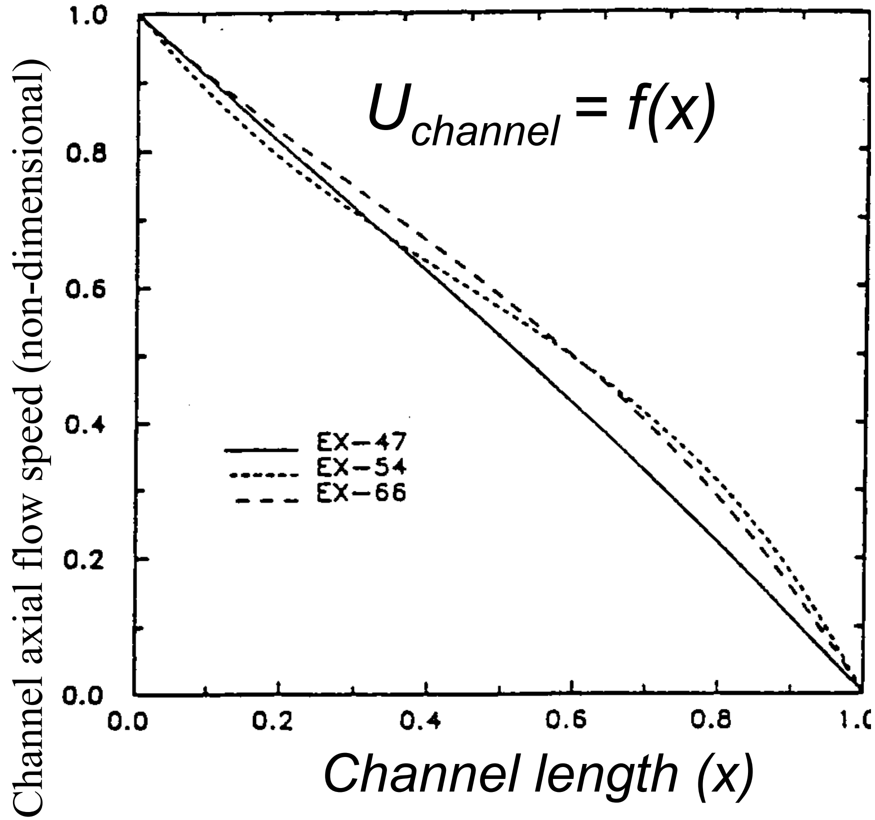
Comparison between Model and Experiment



Filter channel flow: 'axial' and 'wall flow' velocity components



Change in the wall-flow velocity component (non-dimensional) along the channel length. The velocity change depends greatly on the wall permeability*.



Change in the axial velocity component (non-dimensional) along the channel length *.

$U_{wall} / U_{channel} \sim 10^{-2} - 10^{-3}$

From: A.G., Konstandopoulos and J.H. Johnson, SAE - 1989-890405

Conclusions

• Exhaust gas flow through a wall-flow Diesel Particulate filter experiences several different flow regimes, each having a unique contribution to the total filter pressure drop.

• It is possible to capture the total filter pressure drop ‘accurately’ using a model that accounts for all individual filter pressure drop contributions. The model has been tested and shown to yield remarkably accurate results.

• The flow through the filter channel has two predominant velocity components -- axial and wall-flow (lateral).

  - The axial component drops nearly linearly to zero along the channel length.
  - The wall-flow component changes non-linearly and its shape depends on the filter wall permeability.

• Hypotheses such as particulates are more deposited in the filter front (or rear) do not agree with physical insight into flow/ particulate transport in the filter channel. More work is needed to explain accurate picture of particulate transport and deposit inside the filter.