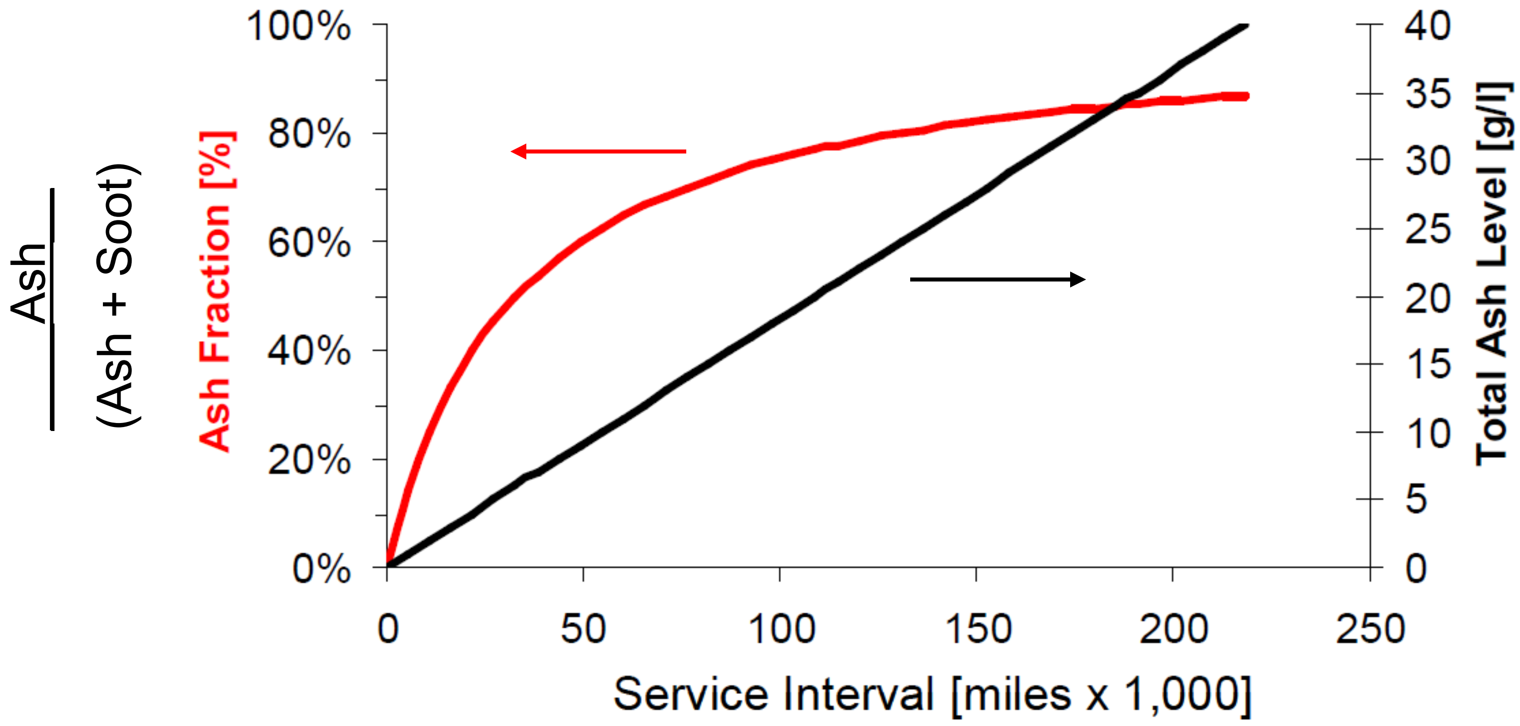
The Sensitivity of DPF Performance to the Spatial Distribution of Ash Generated from Six Lubricant Formulations

Presenter: Yujun Wang
Advisor: Dr. Victor W. Wong
October 18, 2012

Massachusetts Institute of Technology
Sloan Automotive Laboratory Cambridge, MA

Inconvenient Reality

During most of a DPF's useful life (i.e. except at low mileage), there is more "ash" (incombustibles) than soot accumulated in the DPF at any time

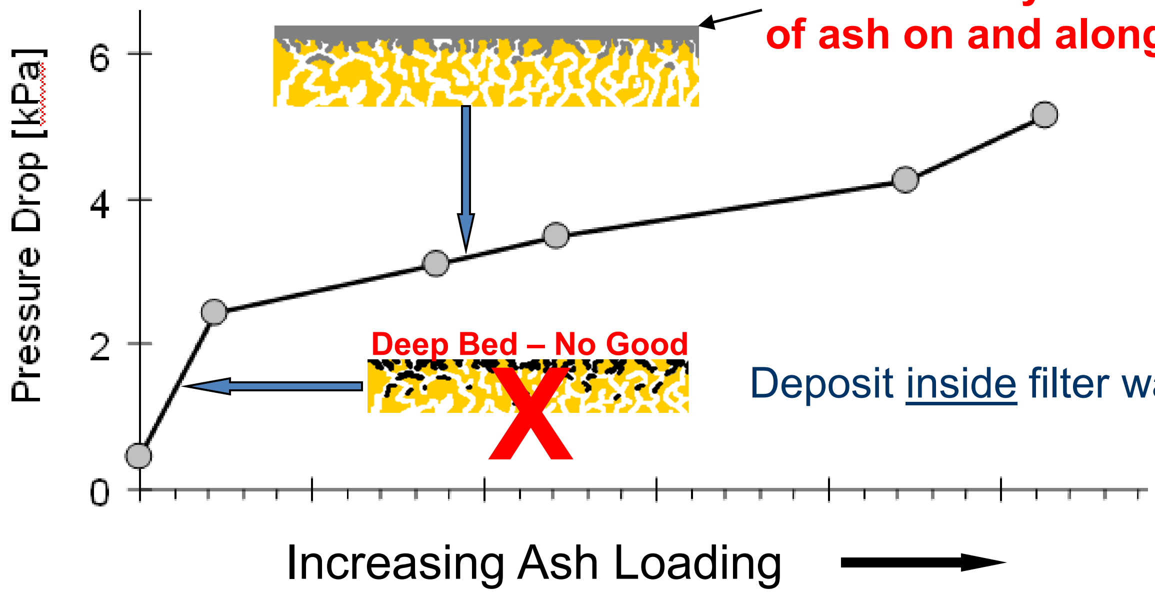


Key Questions

If ash is to stay in the DPF, are there better places than others in the DPF to accommodate the presence of ash?

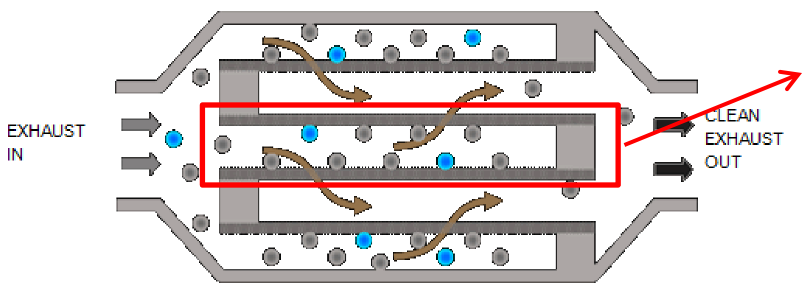
- **Can we localize or quarantine ash to minimize its impact?**
- **What are the sensitivities?**

Current study: Effects of distribution of ash on and along channel walls



Deposit inside filter walls – Not good

Ash Spatial Distribution inside DPF Channel

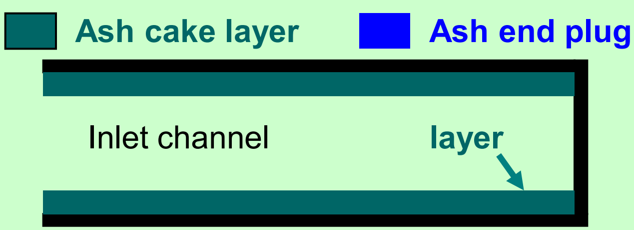


DPF Schematic Picture

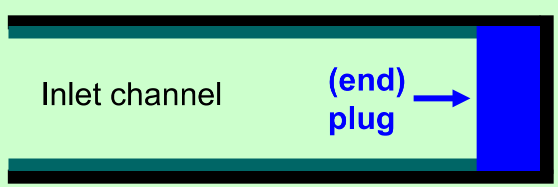
Assuming ash accumulates either on channel walls as layers or at the end of channels as end-plugs

- Ash may deposit with different ash plug length (ash plug ratio)

Definition : $\text{Ash Plug Ratio} = \dfrac{\text{Ash Plug Mass}}{\text{total Ash Mass}}$

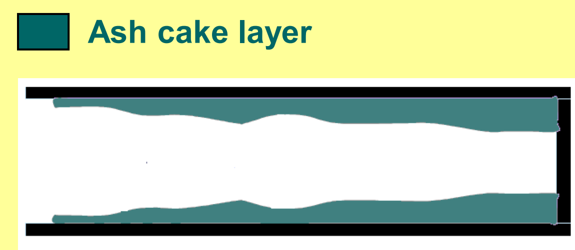


Ash Plug Ratio=0



Ash Plug Ratio=0.5

- Ash may also distribute with certain cake layer profile



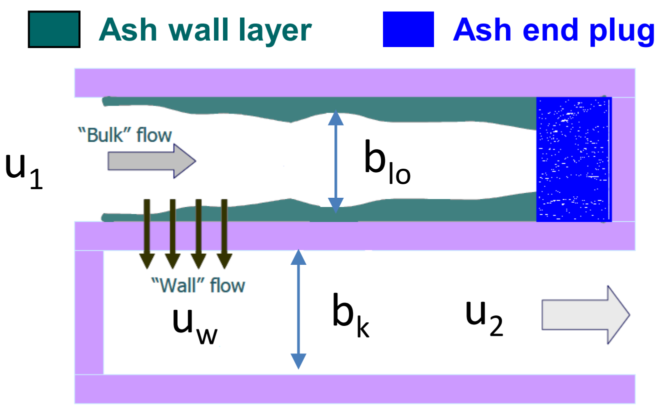
Note : Ash Layer profile have been observed from the experiment conducted at MIT

Study Objectives:

- ✓ What is the effect of ash cake layer profile or ash plug ratio on DPF pressure drop ?
- ✓ How much benefit can be obtained from ash distribution optimization ?

Reformulated DPF Model Considering Ash Layer Profile

Variable-layer-thickness model was improved and implemented in study:



- The original control equations are hard to solve numerically
- Proceeded to solve the transient problem; Pseudo Time Loop is much more robust and efficient

The PDEs on the right is easier to solve than the ODEs on the left.

Need to re-derive the governing equations :

Break into 2 terms

$$\frac{d\left(b_{lo}^2 u_1\right)}{dx} = -4 b_k u_w$$

$$\frac{d\left(b_k^2 u_2\right)}{dx} = -4 b_k u_w$$

$$\rho \frac{d\left(b_{lo}^2 u_1^2\right)}{dx} = -\frac{dP_1}{dx} b_{lo}^2 - F\eta u_1$$

$$\rho \frac{d\left(b_k^2 u_2^2\right)}{dx} = -\frac{dP_2}{dx} b_k^2 - F\eta u_2$$

$$P_1 - P_2 = \eta\left(\frac{s_w}{k_w} + \frac{s_s}{k_s} + \frac{s_a}{k_a}\right) u_w + \rho\left(\beta_w s_w + \beta_s s_s + \beta_a s_a\right) u_w^2$$

Add dt term

$$\frac{d\left(b_{lo}^2 u_1\right)}{dx} = -4 b_k u_w$$

$$\frac{d\left(b_k^2 u_2\right)}{dx} = 4 b_k u_w$$

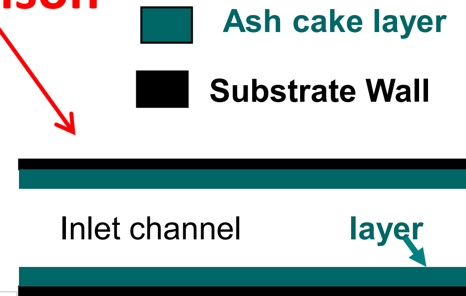
$$\frac{\rho}{b_{lo}^2} \frac{d\left(b_{lo}^2 u_1\right)}{dt} + \frac{\rho}{b_{lo}^2} \frac{d\left(b_{lo}^2 u_1^2\right)}{dx} = -\frac{dP_1}{dx} - \frac{F\eta u_1}{b_{lo}^2}$$

$$\rho \frac{d\left(u_2\right)}{dt} + \rho \frac{d\left(u_2^2\right)}{dx} = -\frac{dP_2}{dx} - \frac{F\eta u_2}{b_k^2}$$

$$P_1 - P_2 = \eta\left(\frac{s_w}{k_w} + \frac{s_s}{k_s} + \frac{s_a}{k_a}\right) u_w + \rho\left(\beta_w s_w + \beta_s s_s + \beta_a s_a\right) u_w^2$$

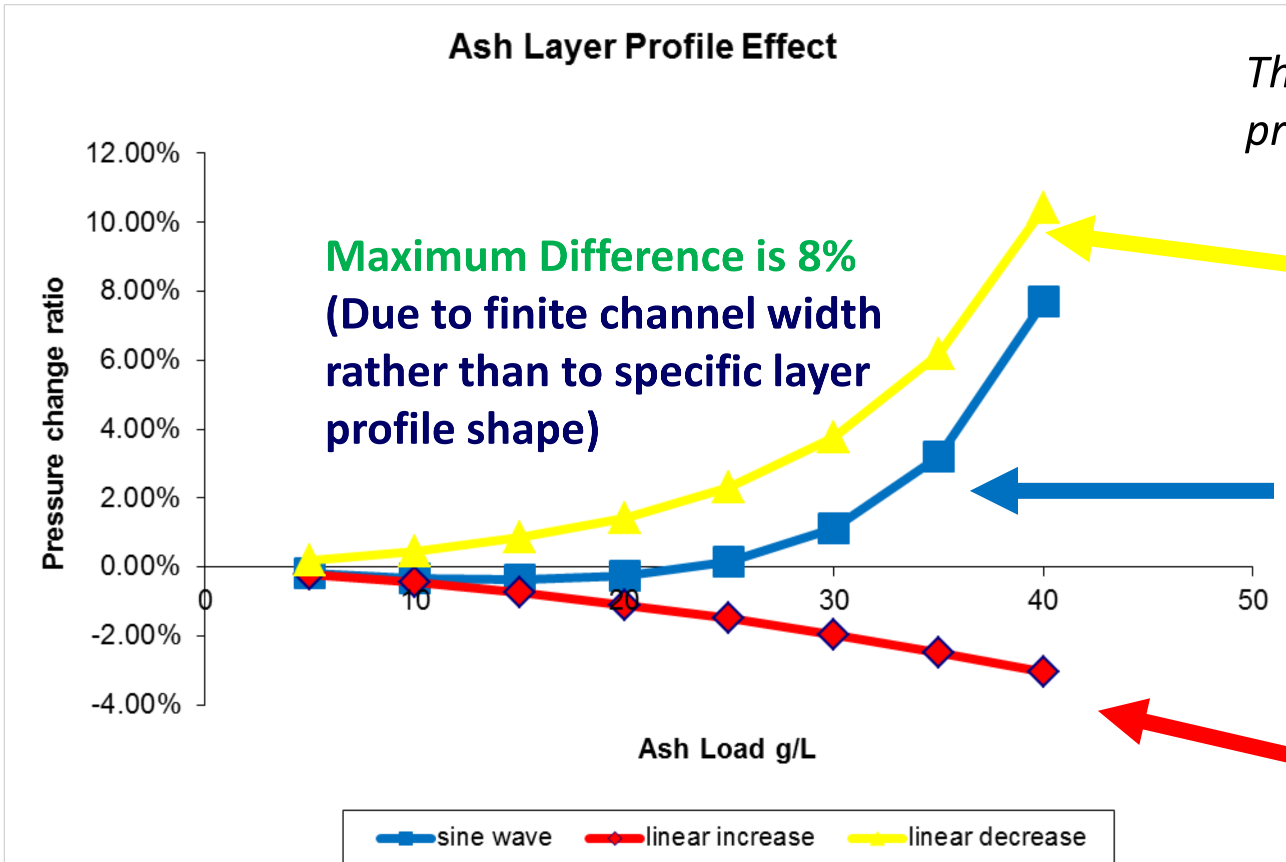
Ash Layer Profile Effect – Relatively Small

Flat Ash Layer Profile is the baseline for the comparison

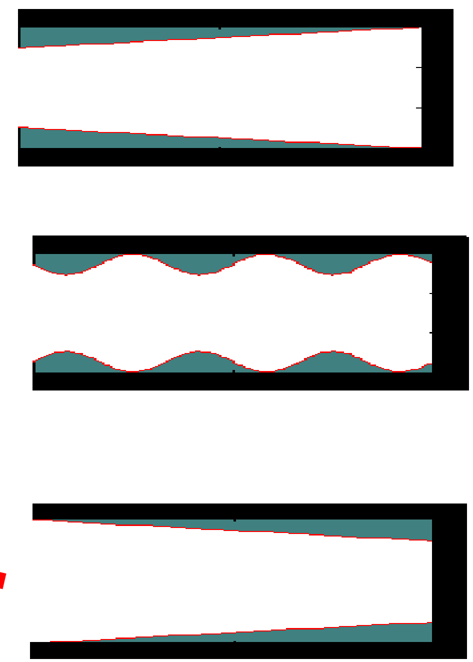


Simulation Parameter: $K_w=5\times10^{-14}\ m^2$; $K_a=1\times10^{-13} m^2$

$$\text{pressure change ratio} = \frac{\Delta P(nonflat) - \Delta P(flat)}{\Delta P(flat)}$$



Three non-flat layer profiles are investigated :



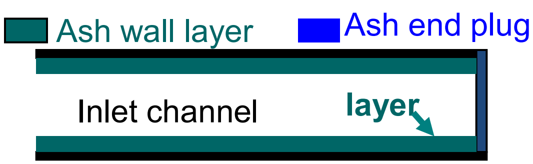
Effects of Ash Plug Ratio on DPF Pressure Drop

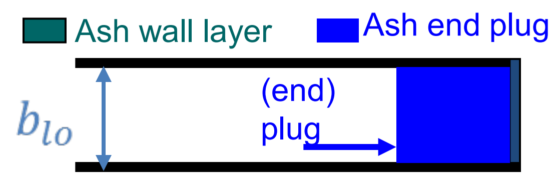
Permeable Layer Pressure Drop

$$\Delta P = \frac{\mu\, u\, \delta}{k}$$

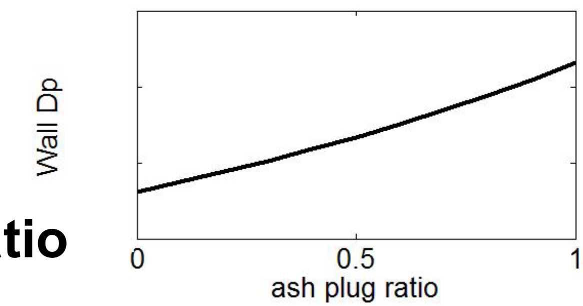
μ – fluid viscosity (constant)
k – layer permeability (constant)
u – flow velocity
δ – layer thickness

As ash plug ratio increases **[x=0, no end-plug; x=1 all end-plug]** **(more ash at channel end):**



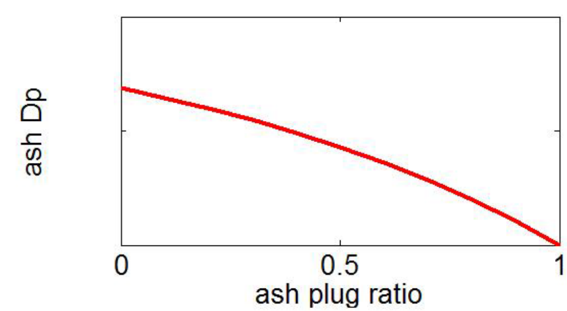


Wall Pressure Drop u_{wall} ↑ δ_{wall} **constant** →



Wall pressure drop increases with ash plug ratio

Ash Layer Pressure Drop u_{wall} ↑ δ_{ash} ↓ →



Ash cake layer pressure drop decreases with ash plug ratio

Effects of Ash Plug Ratio on DPF Pressure Drop

Flow Friction Pressure Drop

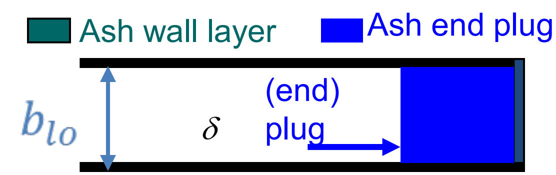
$$\Delta P \sim Q\frac{\mu}{b_{lo}^4}$$

μ – fluid viscosity (constant)

Q – flow volume rate (constant)

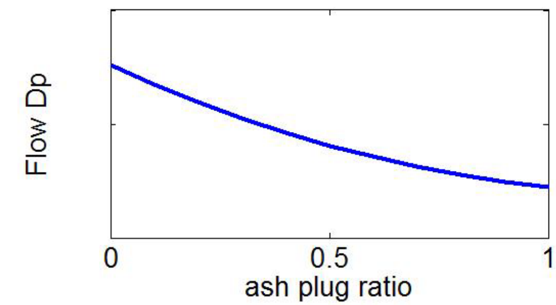
b_{lo} – channel open width

As ash plug ratio increases **[x=0, no end-plug; x=1 all end-plug]** **(more ash at channel end):**



Flow Friction Pressure Drop

b_{lo} ↑ →

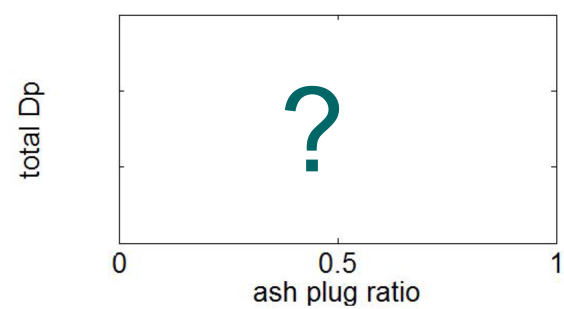


Flow Friction Pressure Drop decreases with ash plug ratio

total Pressure Drop

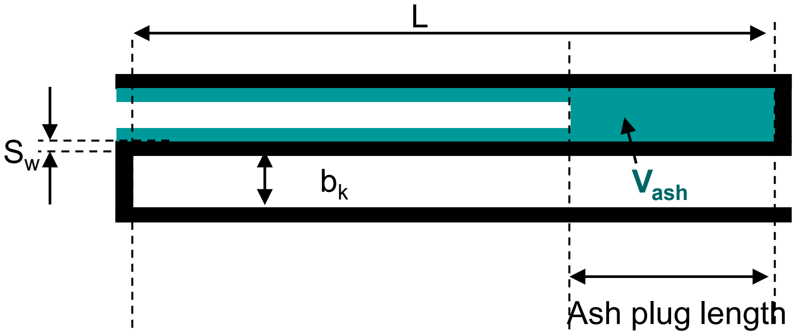
Depend on case parameters affecting pressure drop across ash layer versus that across wall material ?

→



Parametric & dimensional analyses in Ash Plug Ratio Effect:

From the material permeability, geometry and flow parameters,



flow : ~~μ~~ ~~μ_{air}~~

Length : b_k L V_{ash} s_w

permeability : k_a k_w

We derive three non-dimensional parameters that describe the physics under various combinations of parameters:

Material Restriction Ratio

$$= \frac{\text{ash layer restriction}}{\text{wall restriction}} \qquad M = \frac{\dfrac{V_{ash}}{4Lb_k k_a}}{\dfrac{w_s}{k_w}}$$

Geometry Ratio

$$= \frac{\text{ash volume}}{\text{channel volume}} \qquad G = \frac{V_{ash}}{b_k^{\,2} L}$$

Channel Loss Ratio

$$= \frac{\text{flow friction restriction}}{\text{wall restriction}} \qquad C = \frac{\dfrac{F}{3}\dfrac{4L^2}{b_k}\left(\dfrac{1}{b_k^{\,2} - \dfrac{V_{ash}}{L}} + \dfrac{1}{b_k^{\,2}}\right)}{\dfrac{w_s}{k_w}}$$

And define a performance metric and target function:

Target function: Assuming all the ash is deposited layer on the channel wall to start (no end-plu, x=0), evaluate the pressure drop change if one sweeps ALL the ash to the channel end (all end plug, x=1). Normalize it to the initial pressure drop. This measure is the target function, defined as:

$$s = \frac{\Delta P(x=1) - \Delta P(x=0)}{\Delta P(x=0)}$$

$$= \frac{\Delta P_{friction,x=1} + \Delta P_{wall,x=1}}{\Delta P_{friction,x=0} + \Delta P_{wall,x=0} + \Delta P_{ash,x=0}} - 1$$

$$\approx \frac{C\left(1 - \frac{G}{2-G}\right) + \frac{1}{1-G}}{C + M + 1} - 1$$

$$x = \text{Ash Plug Ratio} = \frac{\text{Ash Plug Mass}}{\text{total Ash Mass}}$$

Target Function, s, is:

- **Negative when sweeping all the ash layer to the channel end to form an ash plug reduces pressure drop**
- **Positive when sweeping all the ash layer to the channel end to form an ash plug actually increases the pressure drop**

Typical Results of Analyses

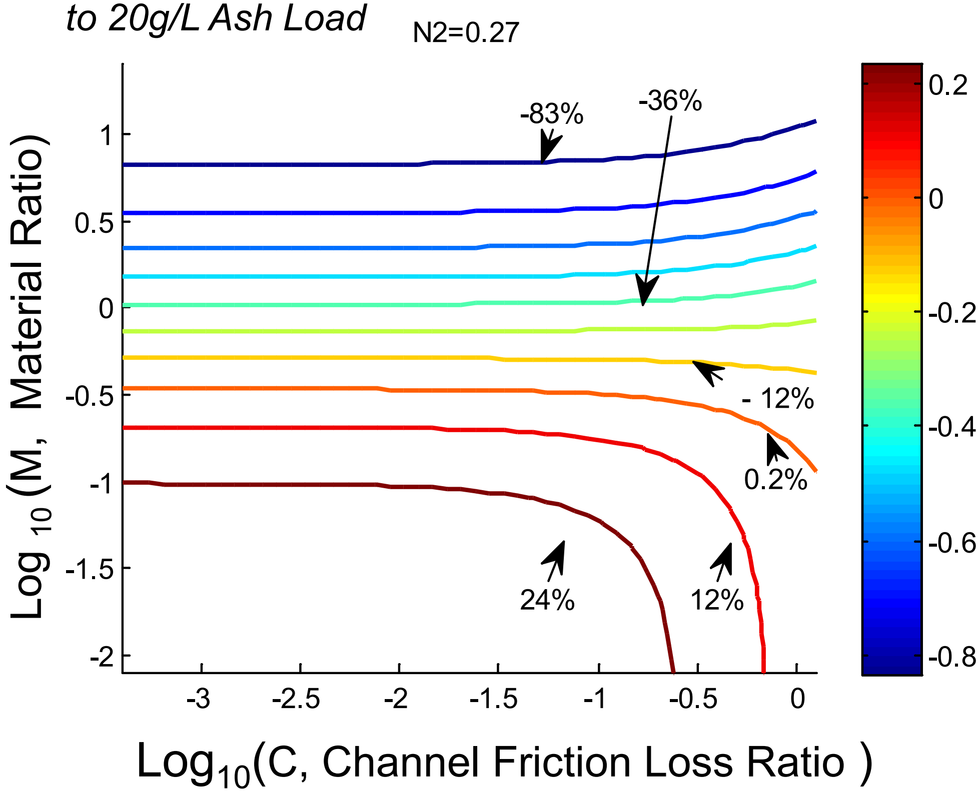
Material Restriction Ratio – M

Geometry Ratio - G

Channel Loss Ratio - C

Target Function $s = \frac{\Delta P(x=1) - \Delta P(x=0)}{\Delta P(x=0)}$

2D contours of S at constant G (N_2)=0.27 corresponding to 20g/L Ash Load



Key Notes:

- Larger M (ash/wall restriction) usually has negative s. Sweep!

Which means moving ash to the end of channel is beneficial when Material Restriction Ratio is very larger

- Small M has positive s

Which means keeping ash on cake layer is beneficial when Material Restriction Ratio is very low

- Contour bends up and down at high C

Ash plug ratio effects become smaller when flow friction pressure drop becomes more important

Where do actual ash + DPFs (with real design parameters) stand on the sensitivity map?

Let's examine actual data from ash collected from six laboratory lubricants:

DPF Performance with Ash Generated from Six Lubricant Formulations

The ash is generated using accelerated ash loading system in Sloan Automotive Lab at MIT

lubricant additives of Ca, Mg, Zn and its combinations are tested individually

Lubricant	Ca	Mg	Zn	P
		ppm		
Base+Ca	2,928	5	<1	2
Base+Mg	<1	2070	<1	<1
Base+Zn	<1	<1	2612	2530
Base+Ca+Zn	2480	<1	1280	1180
Base+Mg+Zn	<1	1730	1280	1180
CJ-4	1388	355	1226	985

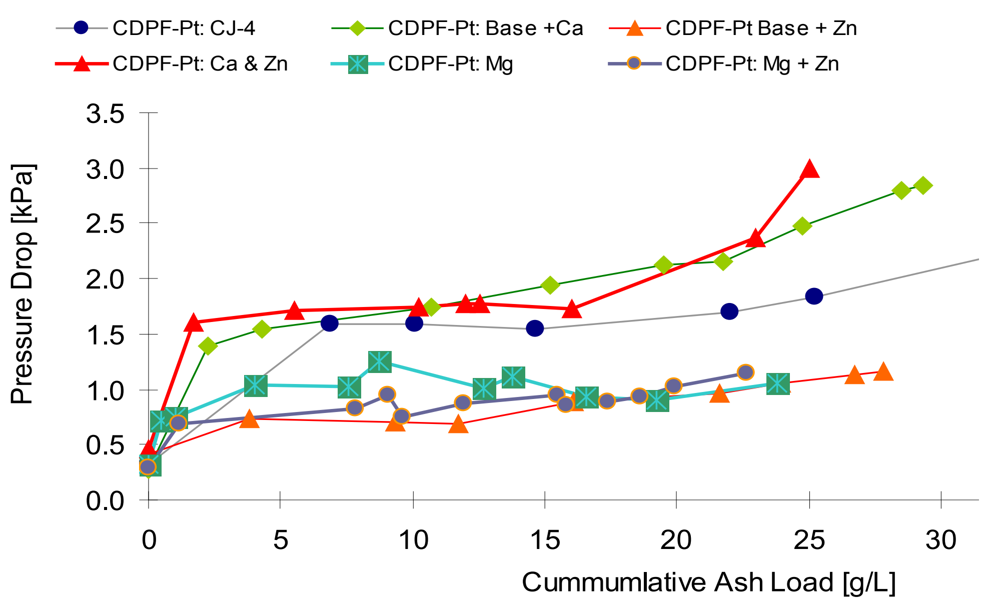
Experiment Condition:

DPF: 6”L 5.66”D 200CPSI

Substrate thickness: 0.012”

Flow: 20,000 1/Hour

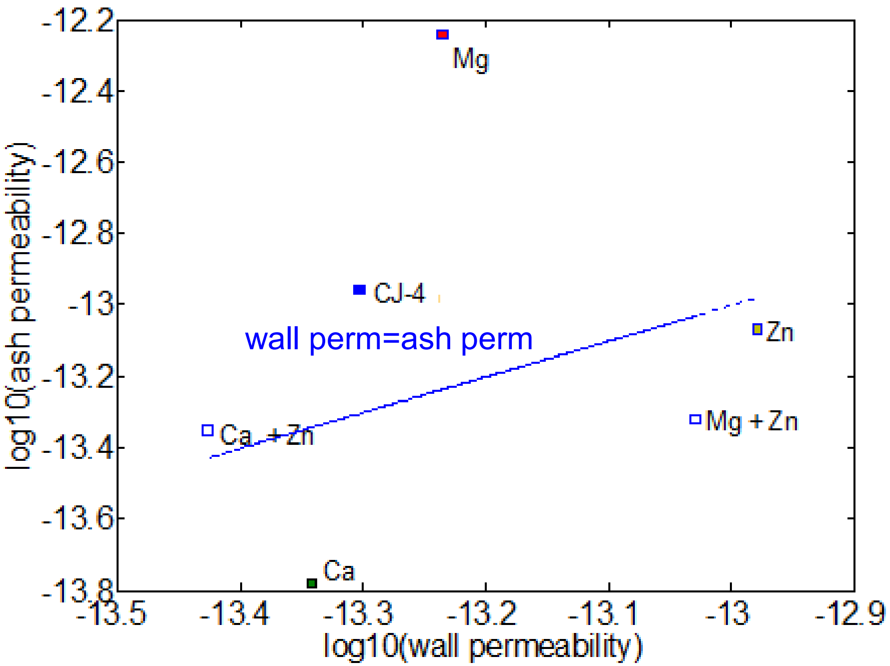
The experimental data is helpful to determine ash and wall permeability



DPF Pressure Drop with ash from different Lubricant additives

Permeability Estimation Result from Experimental Data

Wall/Ash Permeability



- ❑ Here, only discuss the wall permeability after depth filtration .
- ❑ The permeabilities of ash generated from 6 lubricant chemistry are different

- Mg Ash has highest permeability
- Ca Ash has lowest permeability

Typical Estimated Result

Lubricant Additive	Ash Permeability m^2	Wall Permeability m^2
Ca	1.67E-14	4.56E-14
Mg	5.74E-13	5.82E-14

The data is necessary for the non-dimensional analysis

Material Restriction Ratio

$$M = \frac{\dfrac{V_{ash}}{4L b_k k_a}}{\dfrac{w_s}{k_w}}$$

Geometry Ratio

$$G = \frac{V_{ash}}{{b_k}^2 L}$$

Channel Loss Ratio

$$C = \frac{\dfrac{F}{3}\dfrac{4L^2}{b_k}\left(\dfrac{1}{{b_k}^2 - \dfrac{V_{ash}}{L}} + \dfrac{1}{{b_k}^2}\right)}{\dfrac{w_s}{k_w}}$$

Once we get the non-dimensional numbers, we can determine Target Function s in the (M,C) plane

Typical Results of Analyses

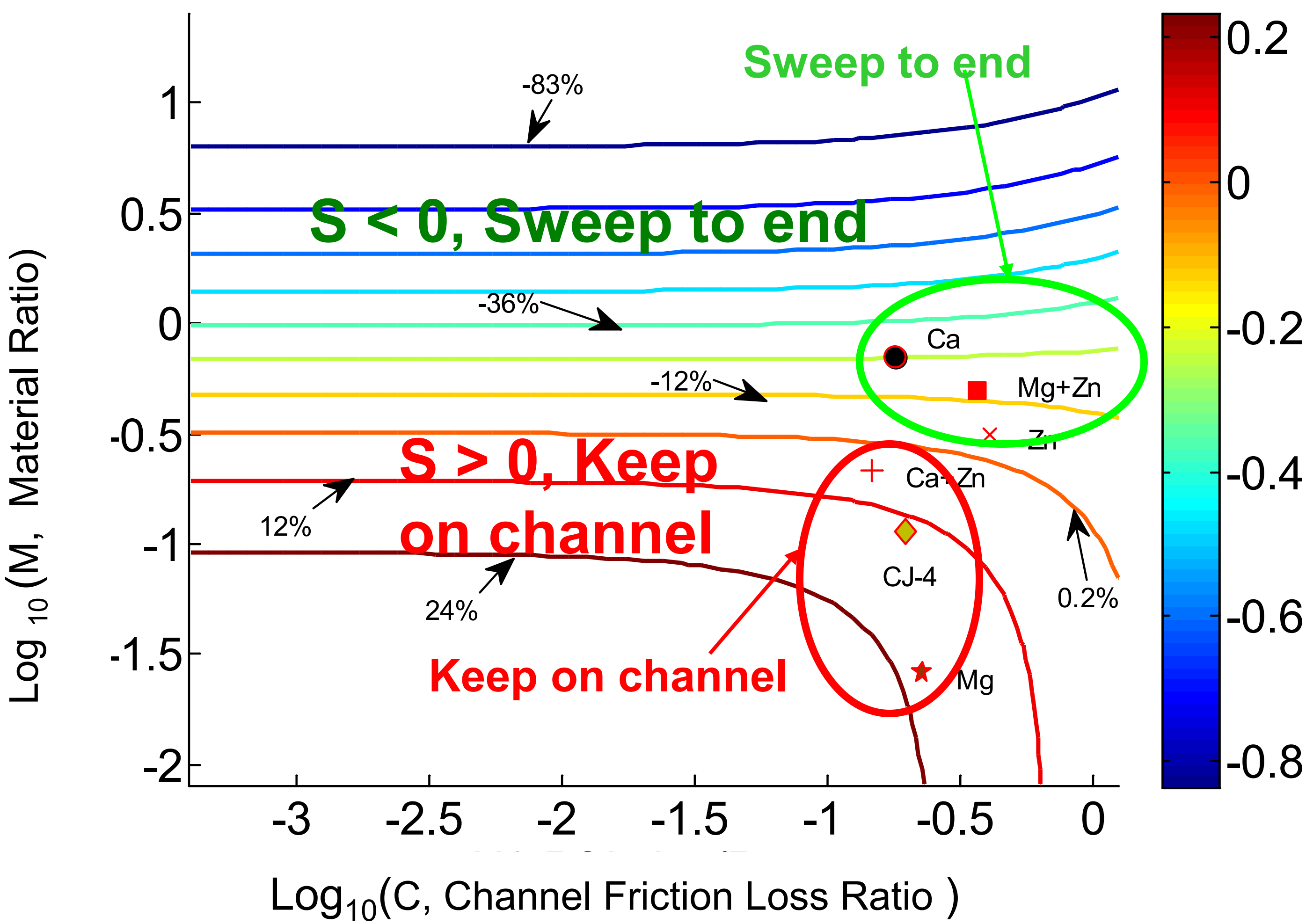
Material Restriction Ratio – M, Geometry Ratio - G

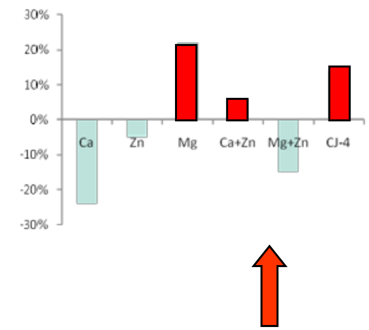
Channel Loss Ratio - C

Target Function $s = \dfrac{\Delta P(x=1) - \Delta P(x=0)}{\Delta P(x=0)}$

2D contours of S at constant G (N_2)=0.27 corresponding to 20g/L Ash Load

N2=0.27





Pressure change ratio

Typical Results of Analyses

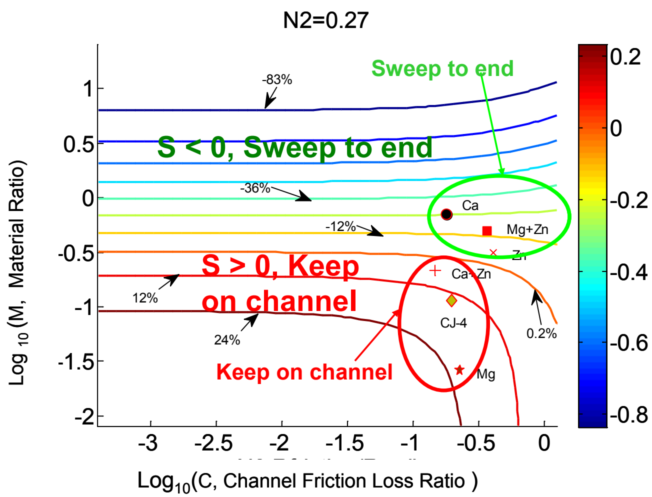
Material Restriction Ratio – M

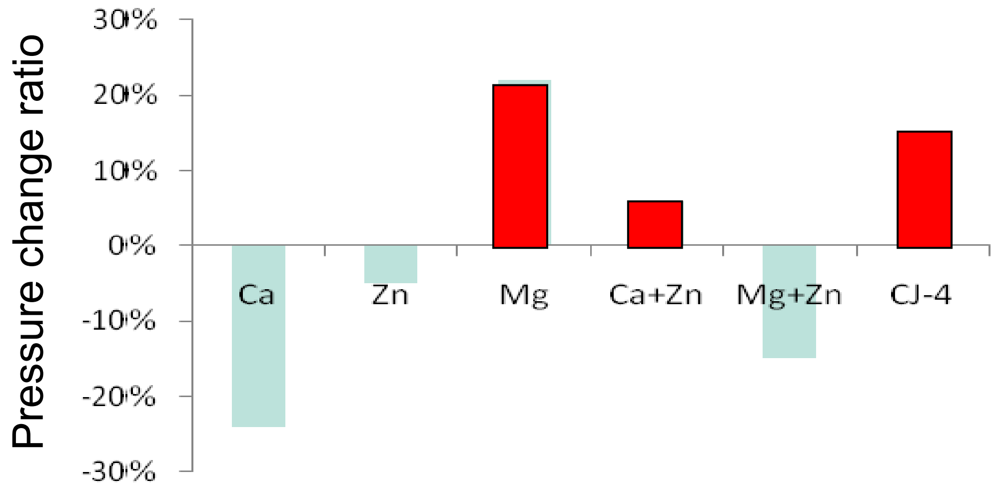
Channel Loss Ratio - C

Geometry Ratio - G

Target Function $s = \frac{\Delta P(x=1) - \Delta P(x=0)}{\Delta P(x=0)}$

2D contours of S at constant G (N_2)=0.27 corresponding to 20g/L Ash Load





Pressure change ratio for the six lubricants tested

Conclusions

Bottom Line (a/k/a Last Page)

- **The precise shape of the ash distribution profile along the channel has a small, insignificant effect on pressure drop**
- **No definite, conclusive benefit of accumulating ash at the channel end versus along channel wall can be made. It depends on the ash properties, which vary with lubricant chemistry, as well as on DPF wall materials and design, and on flow conditions**

Details:

- 1-D model considering ash cake layer profile suggests that the effect of ash cake layer profile on DPF pressure drop is generally less than 8%, which is not significant.
- Ca/Zn/Mg+Zn Ash decrease pressure drop if increase the ash plug ratio. For Ca ash, the typical number is -24% @ 20g/L
- Mg/Ca+Zn/CJ-4 Ash increase pressure drop if increase the ash plug ratio. For CJ-4 ash, the typical number is +14% @ 20g/L

→ Inconclusive, pending verification