Gasoline Particulate Filter (GPF) Modeling and Multi-Objective Optimization Investigation

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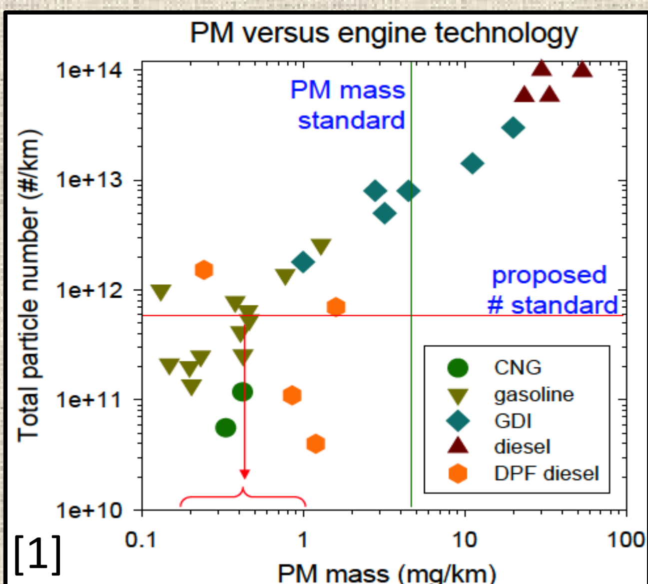
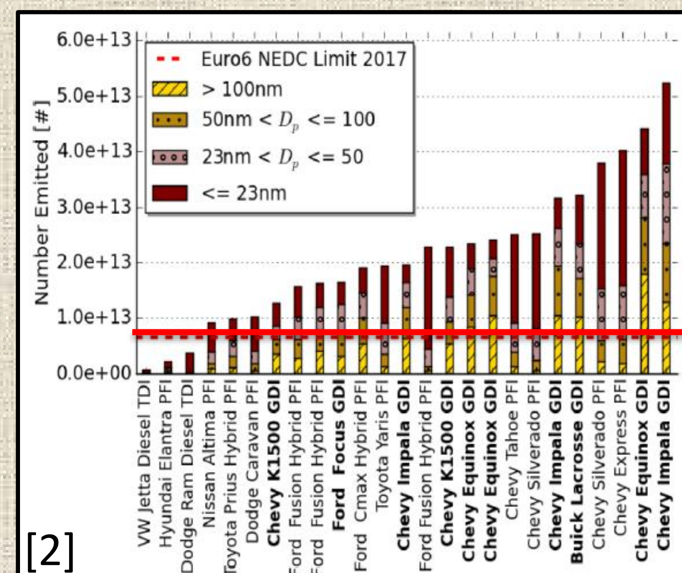
Motivation

- The pursuit of higher fuel efficiency and power from IC engines has led to the rapid development of combustion strategies, such as gasoline direct injection (GDI).
- GDI has higher particulate matter (PM) and particle number (PN) emissions than port fuel injection (PFI). [1]
- Ceramic wall-flow exhaust filters are one way to control PM and PN in gasoline exhaust.
- Gasoline particulate filters (GPFs) are different from diesel particulate filters (DPFs).
  - ➢ PM from GDI engine is lower in concentration than diesel [1]
  - ➢ GDI vehicles are more sensitive to back pressure, cost, and weight
  - ➢ GPFs often need a three-way catalytic coating for four-way functionality



[1]

There is need for GDI-specific PFs with high filtration efficiency and low pressure drop, to meet the EURO 6 or similar PN regulations.[2]

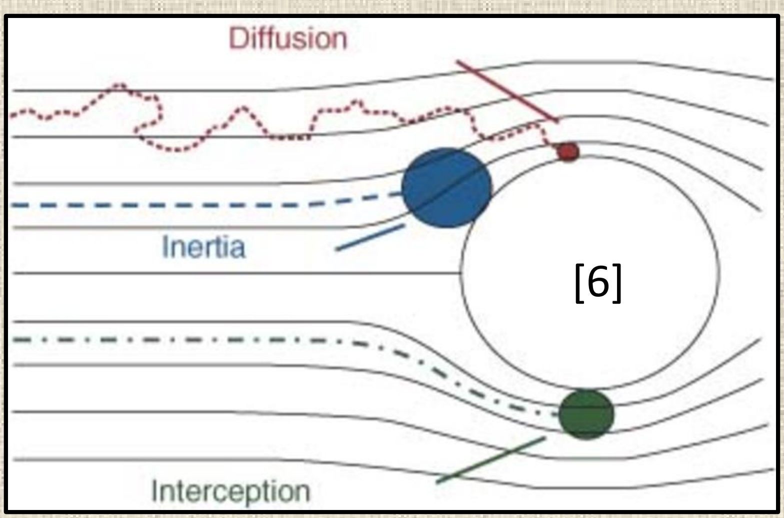


[2]

[1] Maricq, M. *How are emissions of nuclei mode particles affected by emission control*. in *HEI-conference May*. 2009.
[2] Badshah, H., Kittelson, D., and Northrop, W., *Particle Emissions from Light-Duty Vehicles during Cold-Cold Start*, SAE Int. J. Engines 9(3):1775-1785, 2016, doi:10.4271/2016- 01-0997.

Background

- The analytical solution for DPF flow fields and regeneration was derived by Bissett [3], which set up a solid foundation for later DPF and GPF modeling.
- Unit collector model by Konstandopolous and Johnson [4], incorporated with the packed bed theory proposed by Payatakes [5] are still widely used in DPF and GPF filtration modeling. Both models have been validated by numerous experiments.



- Both models are used in this study with modification for the porous wall microstructure study of GPF and 3D filtration study.

[3] Bissett, E., *Mathematical model of the thermal regeneration of a wall-flow monolith diesel particulate filter.* Chemical Engineering Science, 1984. 39(7-8): p. 1233-1244.
[4] Konstandopoulos, A.G. and J.H. Johnson, *Wall-flow diesel particulate filters—their pressure drop and collection efficiency*. 1989, SAE Technical Paper.
[5] Payatakes, A.C., C. Tien, and R.M. Turian, *A new model for granular porous media: Part I. Model formulation.* AIChE Journal, 1973. 19(1): p. 58-67.
[6] G. Muntean, George & L. Stewart, Mark & Devarakonda, Maruthi. *Solid/Condensed Phase Aftertreatment Systems*. 2014

Model Platform Selection

GPF Study	CFD (ANSYS FLUENT)	Analytical Study
0D/1D solution	✔	✔
2D solution	✔	✔
3D solution	✔	○
Detailed flow field	✔	○
Particle tracking	✔	○
Enable microstructure study	✔	○

✔ Good! ○ Insufficient

Approach

Two Objectives:

1. High Filtration Efficiency
2. Low Pressure Drop

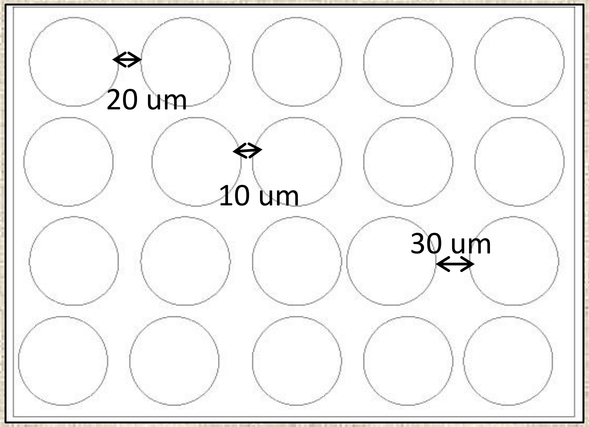
Three areas of research interest:

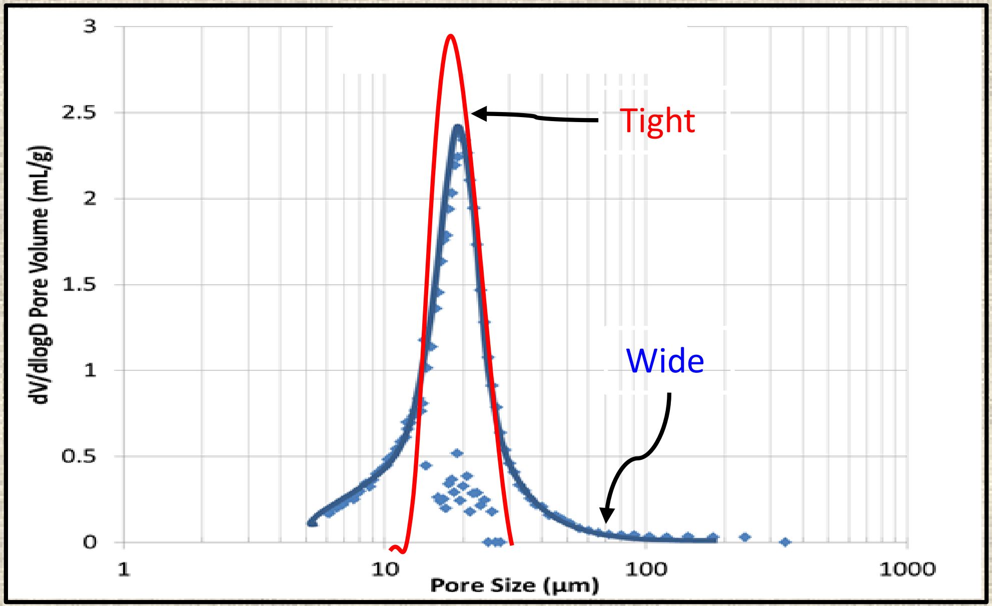
1. Pore size and distribution effects
2. Effect of pore structure
3. Permeability uniformity effects

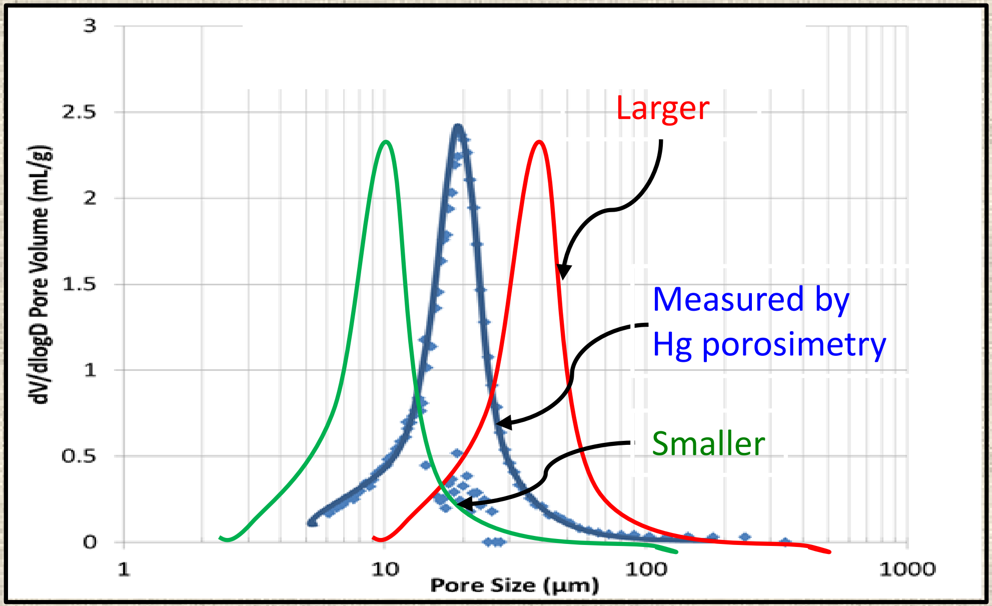
1. Pore Size and Distribution

FLUENT Setup

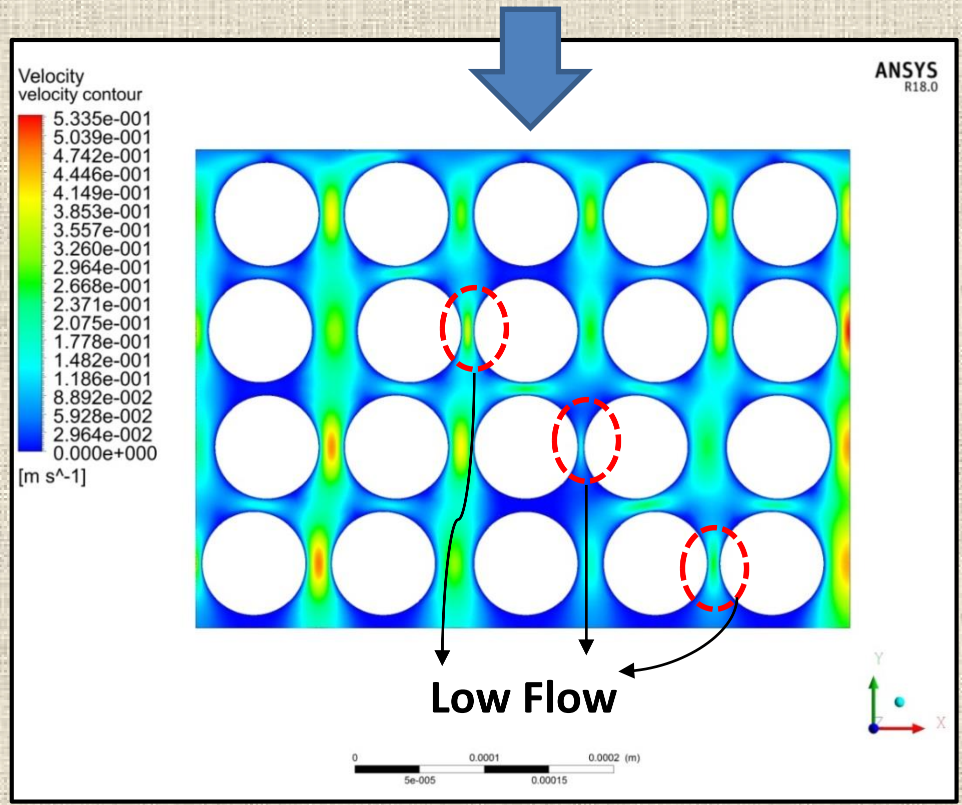
- Steady state study
- Incompressible flow
- Laminar flow
- Boundary conditions:
  - Velocity inlet: 5 cm/s
  - Pressure outlet: 1 atm
- Injected particle size
  - 100 nm



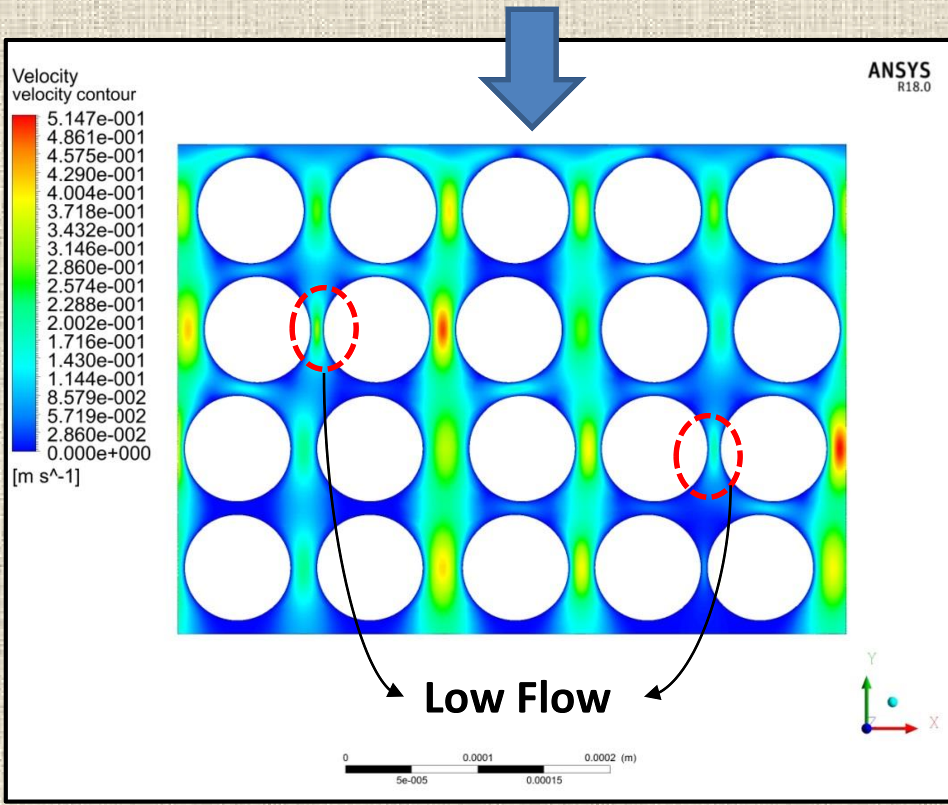




Velocity Field

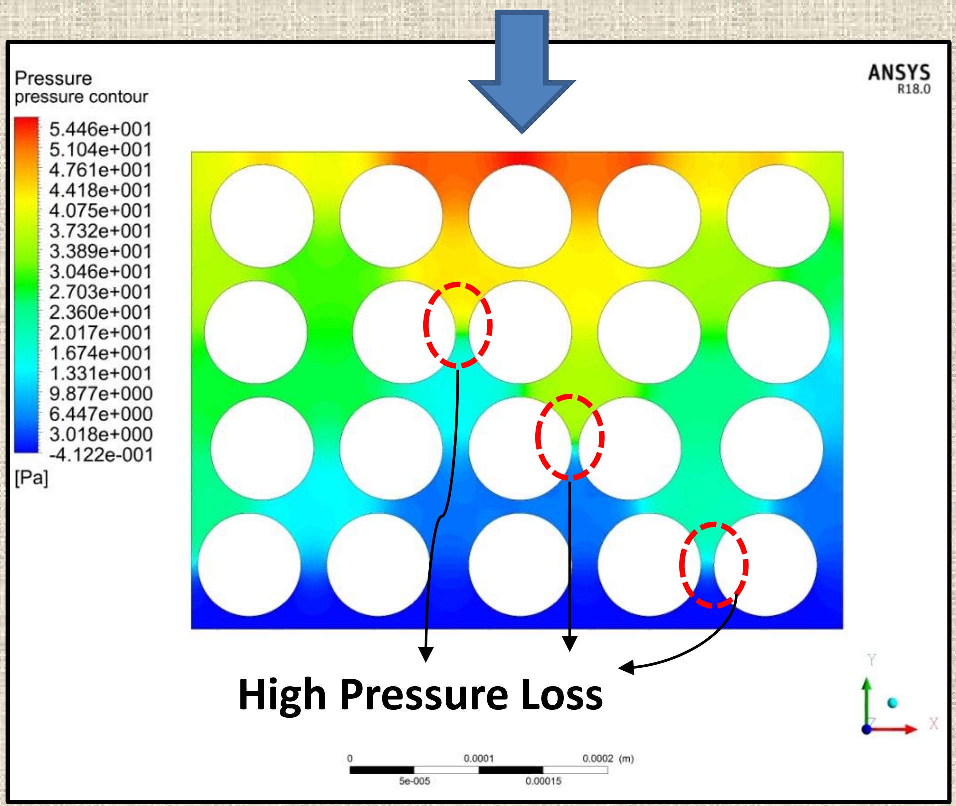


Wide Pore Distribution



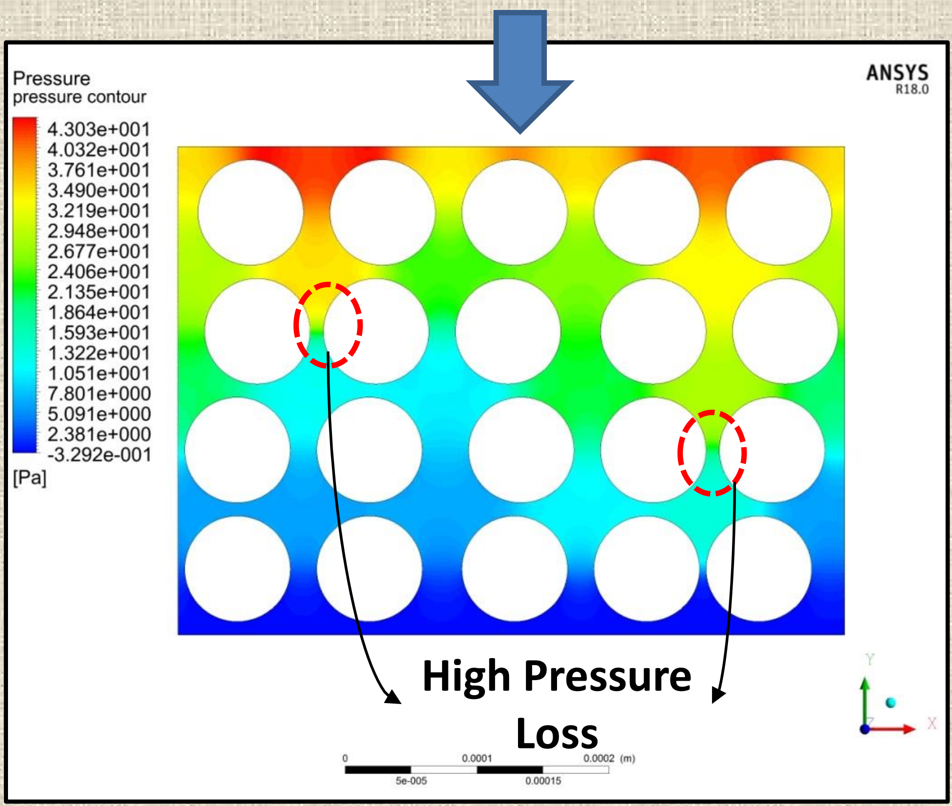
Tight Pore Distribution

Pressure Field



Wide Pore Distribution

ΔP=54 Pa

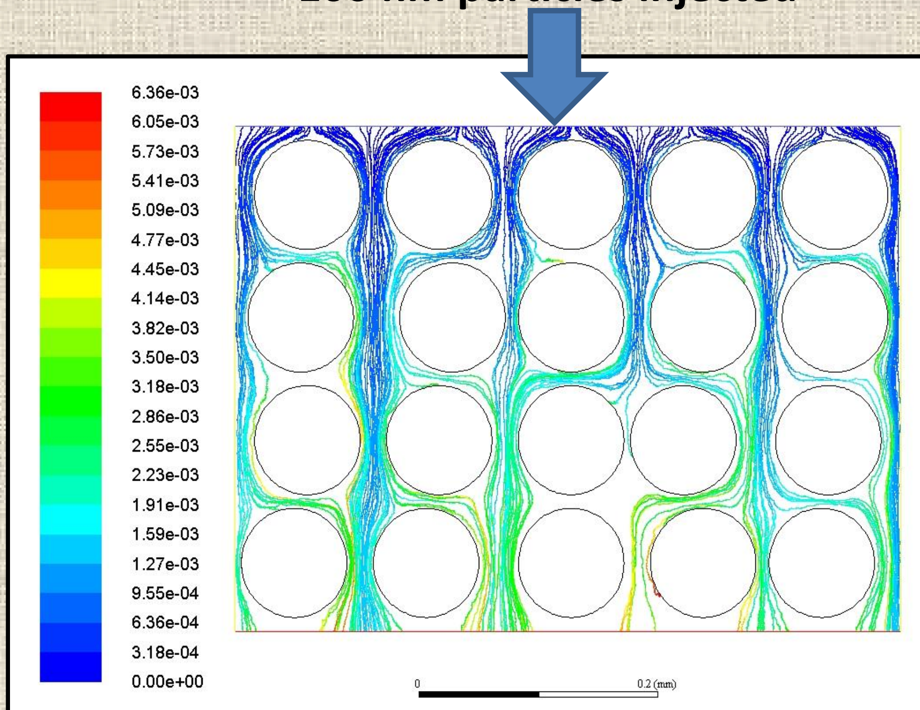


Tight Pore Distribution

ΔP=43 Pa

Particle Tracking

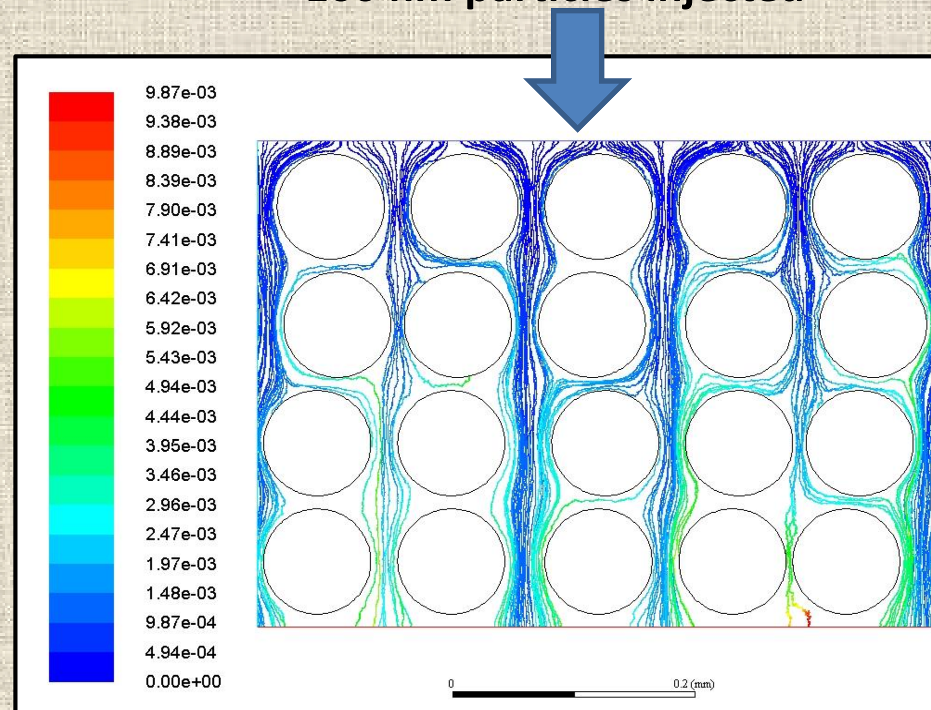
100 nm particles injected



Wide Pore Distribution

Filtration Efficiency $E = 24\%$

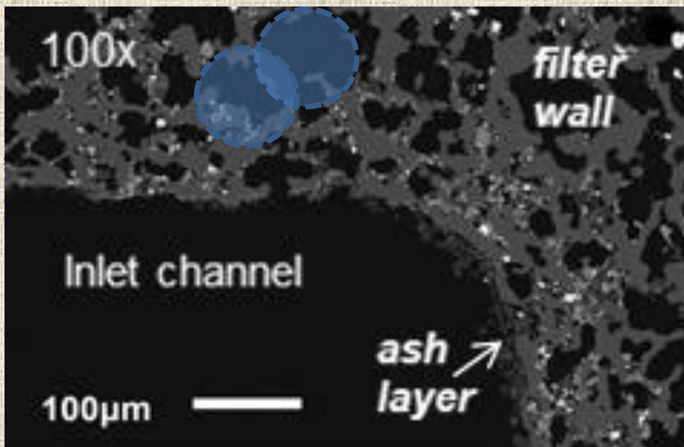
100 nm particles injected



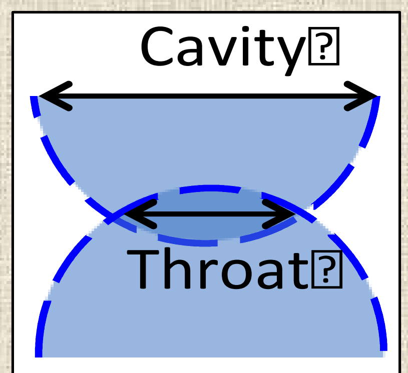
Tight Pore Distribution

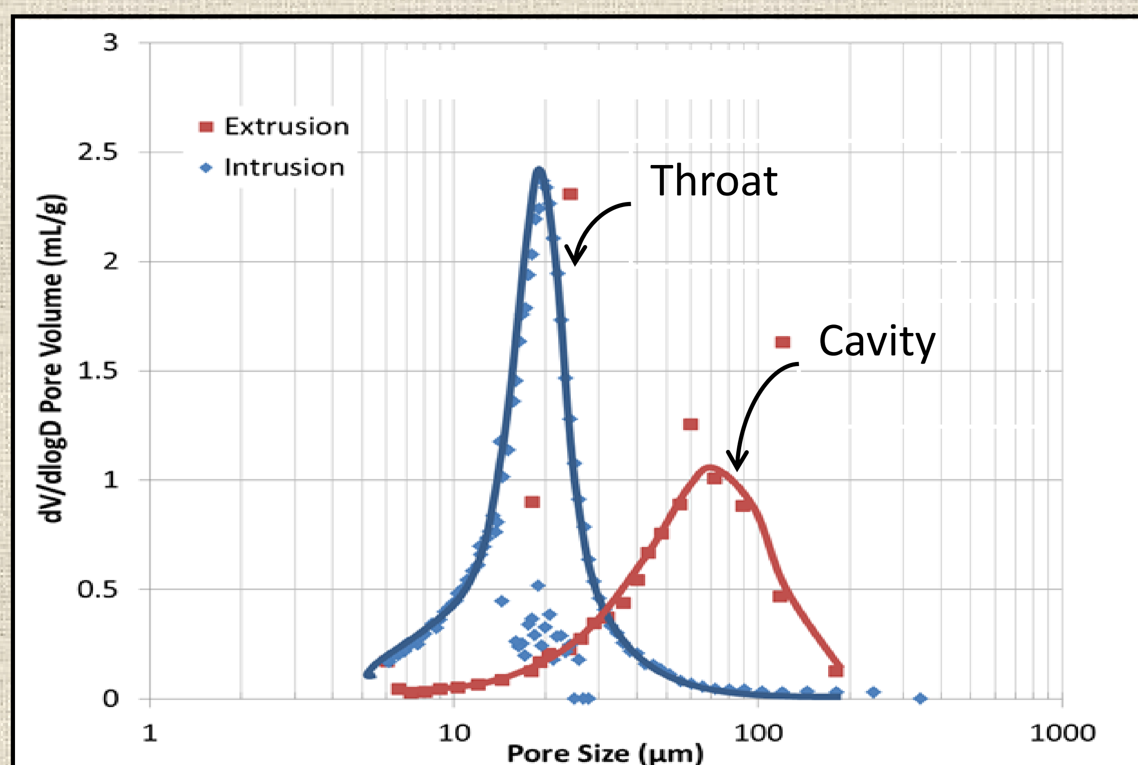
Filtration Efficiency $E = 18\%$

2. Effects of Pore Structure



SEM image of the substrate[7]





The cavity to throat ratio indicates that the throat is the key length scale.

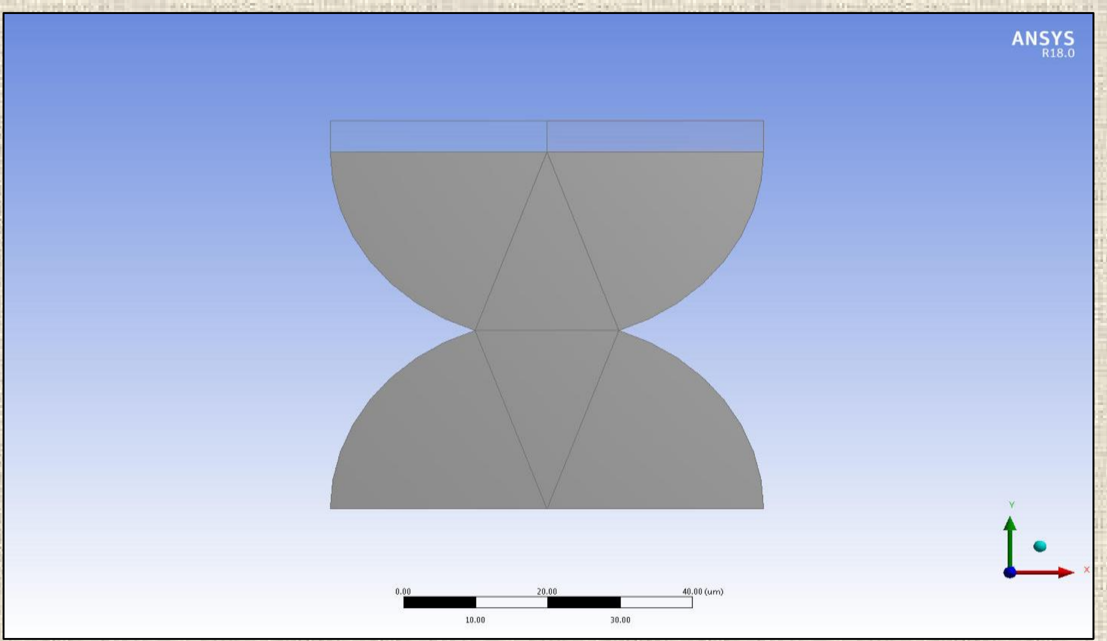
[7] Lambert, C., Bumbaroska, M., Dobson, D., Hangas, J. et al., *Analysis of High Mileage Gasoline Exhaust Particle Filters,* SAE Int. J. Engines 9(2):1296-1304, 2016

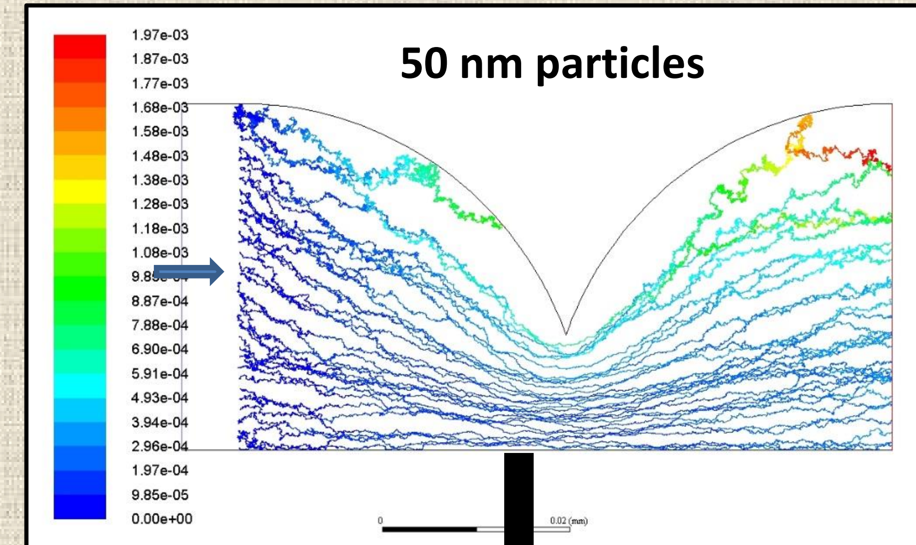
Throat Unit Collector

FLUENT Setup

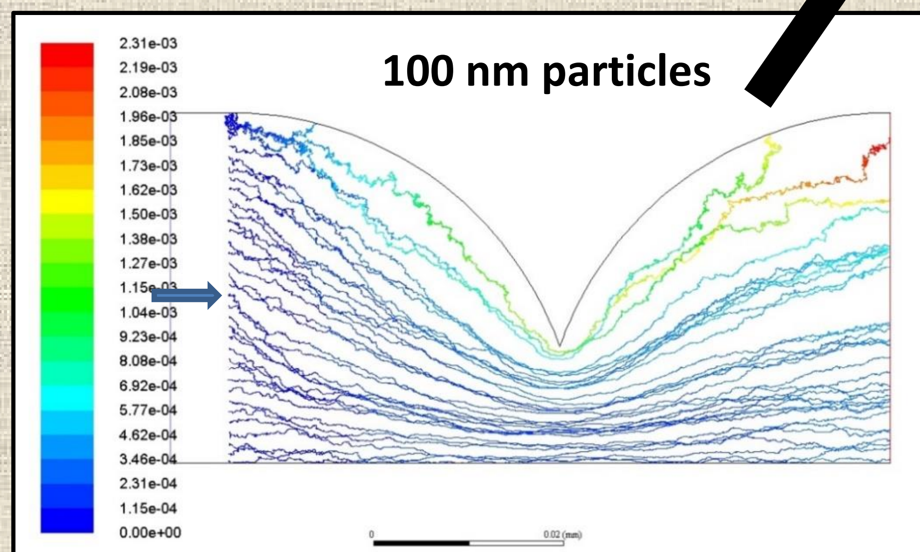
- Axis-symmetric simulation
- Virtual surface (one radius from wall) is introduced to account for the particle capture by interception
- Steady state study
- Incompressible flow
- Laminar flow
- Boundary conditions:
  - Velocity inlet 5 cm/s
  - Pressure outlet 1 atm
- Injected particle sizes:
  - 100 nm
  - 50 nm/300 nm

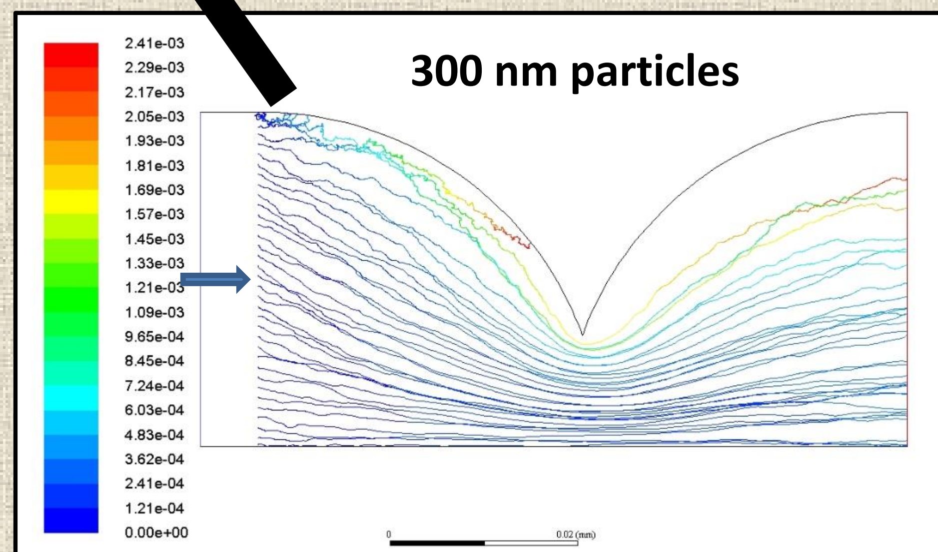
Diameter Ratio	Throat Diameter	Cavity Diameter
5:1	20 um	100 um
3:1	20 um	60 um
2:1	20 um	40 um
1.5:1	20 um	30 um
1:1	20 um	20 um





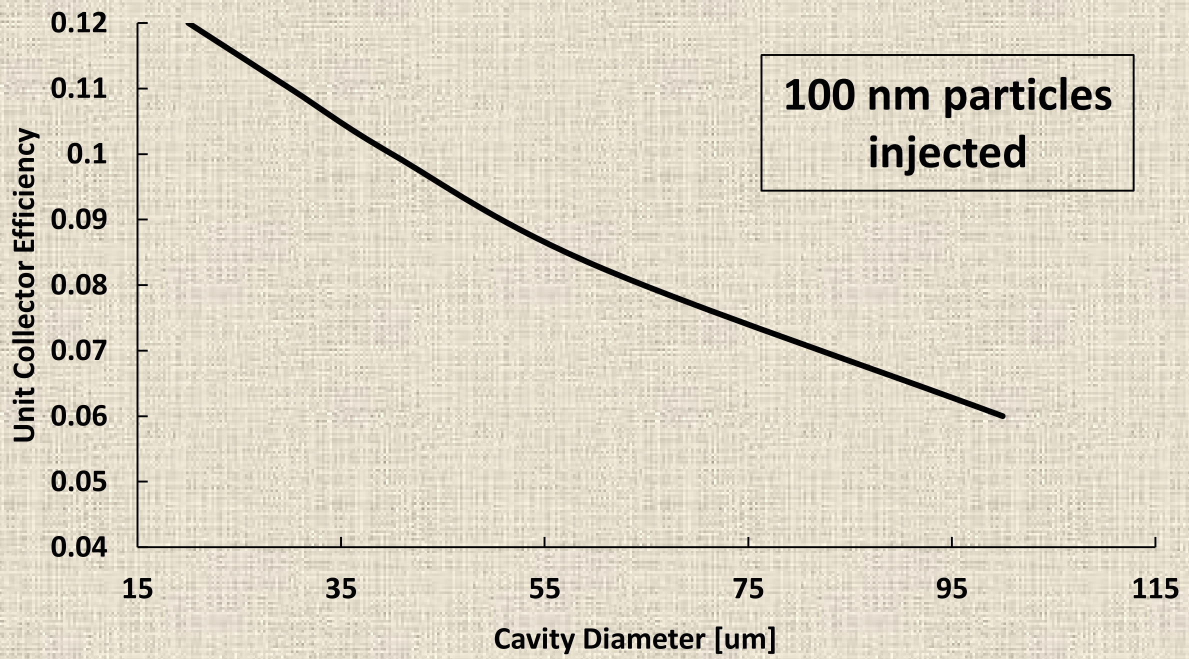
$$h = \frac{Number\ of\ \ Particles\ Trapped}{Number\ of\ \ Particles\ Injected}$$





Filtration Efficiency Increases with Decreasing Cavity Diameter

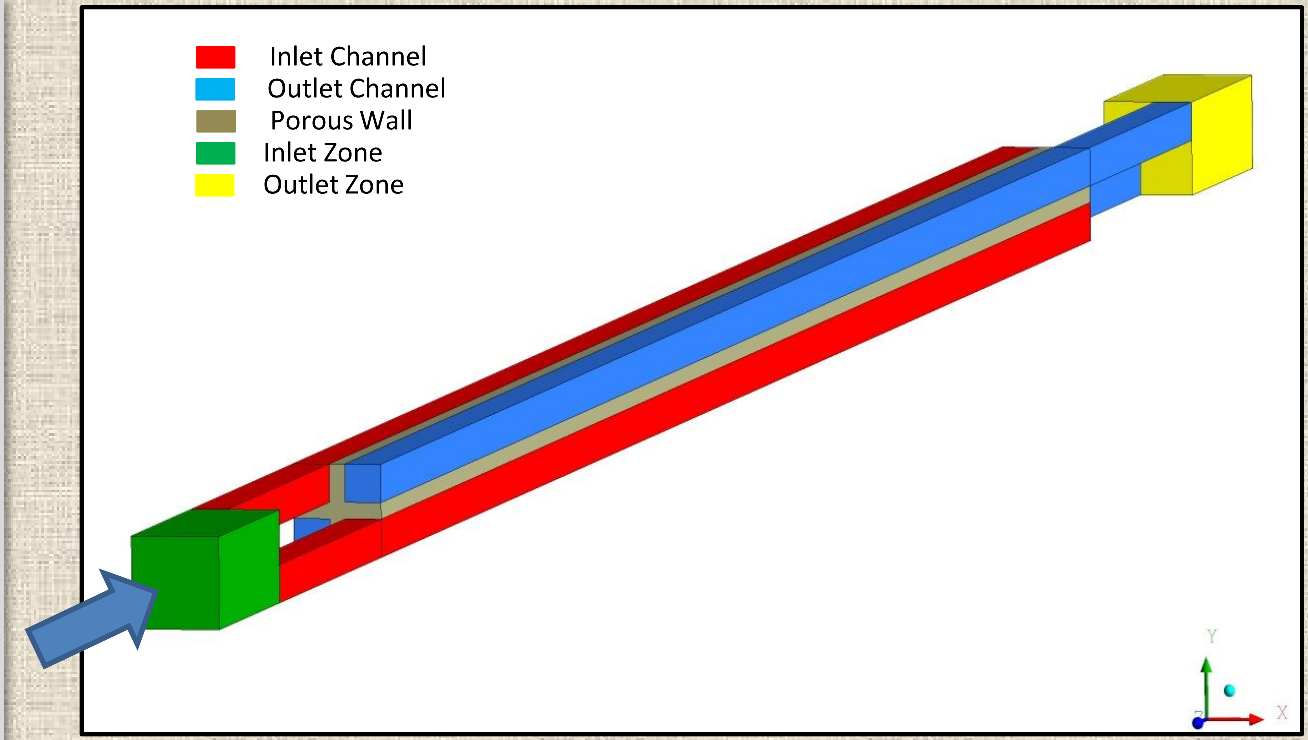
Diameter Ratio	Throat Diameter	Cavity Diameter
5:1	20 um	100 um
3:1	20 um	60 um
2:1	20 um	40 um
1.5:1	20 um	30 um
1:1	20 um	20 um



3. Permeability Uniformity Effects

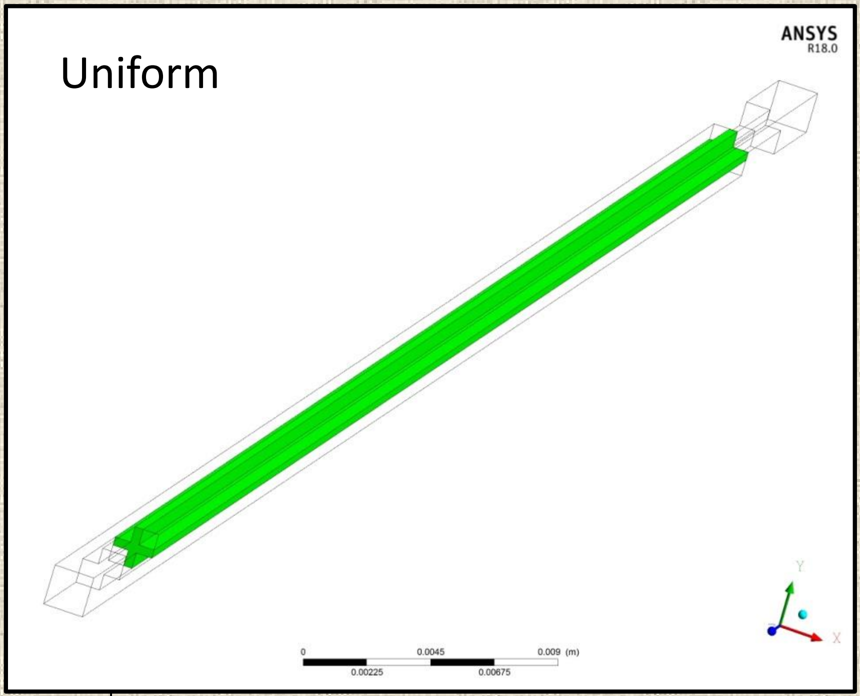
FLUENT Setup

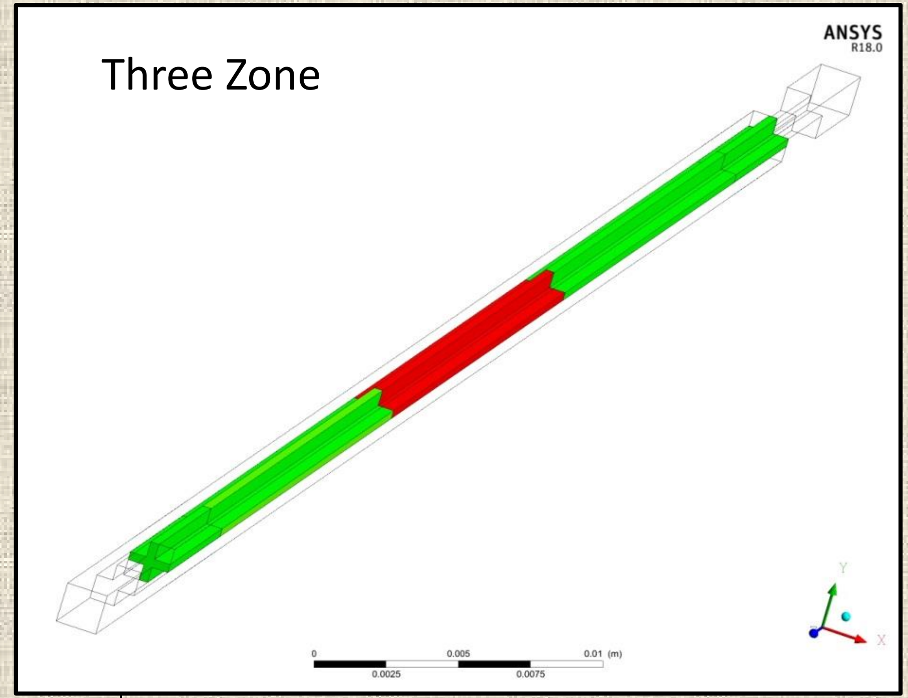
- Steady state, incompressible, laminar flow
- Boundary conditions:
  - ➢ Velocity inlet: 2.226m/s (based on working condition of 60 kg/hr, 500 C)
  - ➢ Outlet P: 1 atm
- Particle injection:
  - ➢ 100 nm, 648 kg/m^3

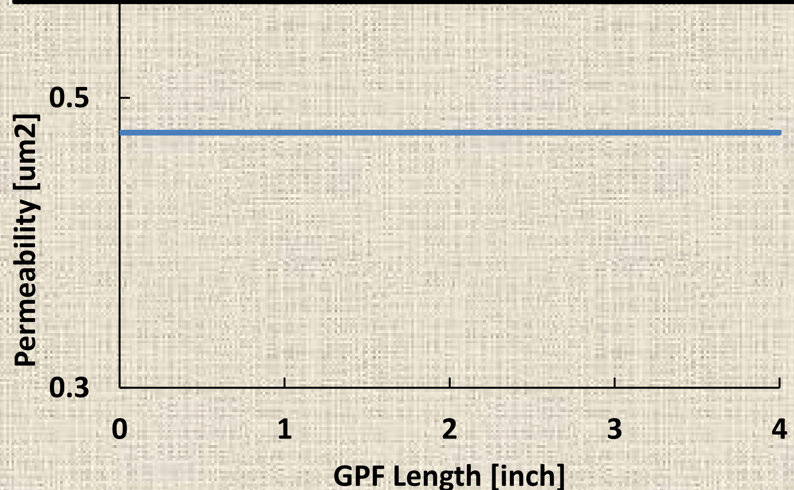


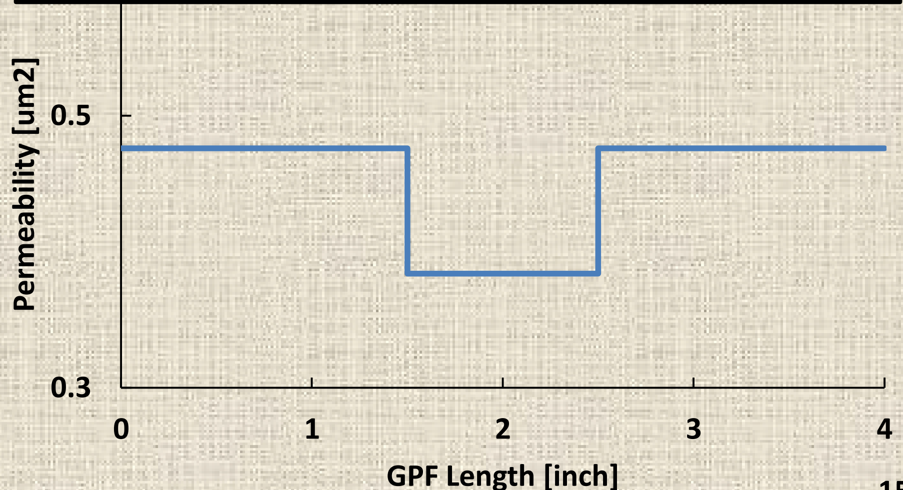
GPF Specifications	
Cell density	300 CPSI
Wall thickness	12 mil
Plug length	5 mm
Inlet/Outlet zone length	5 mm

Wall Permeability Distribution

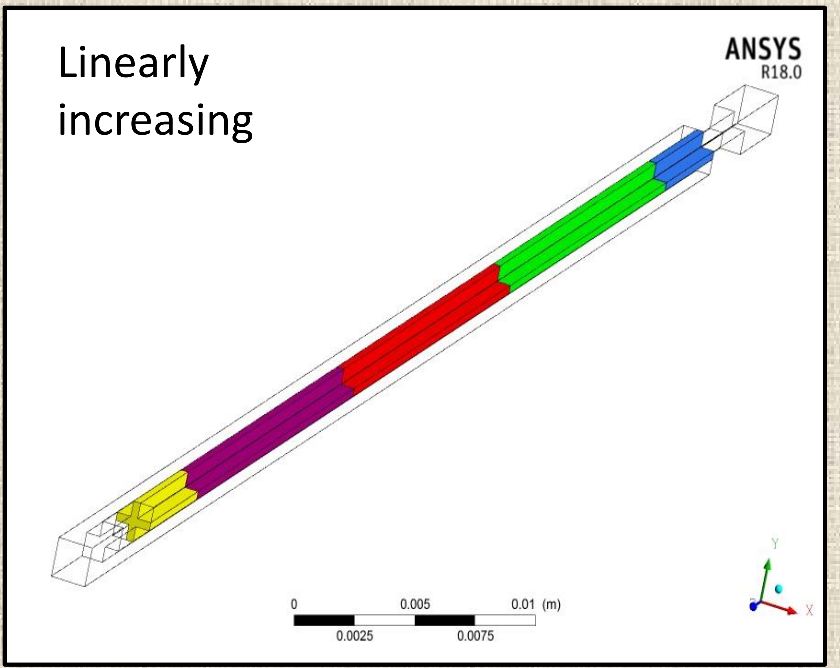


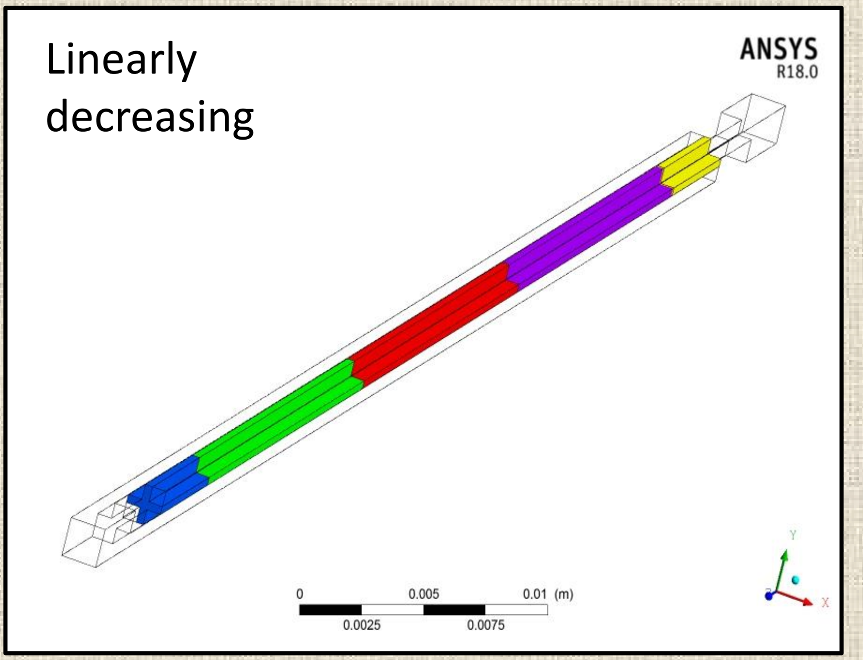


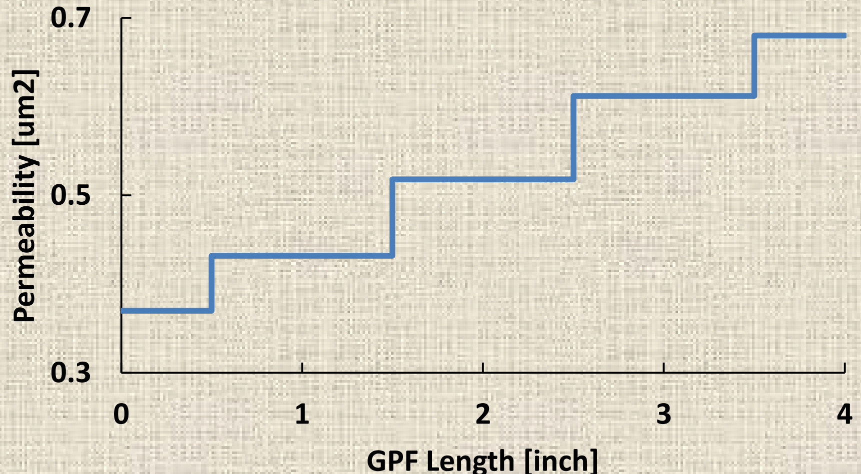


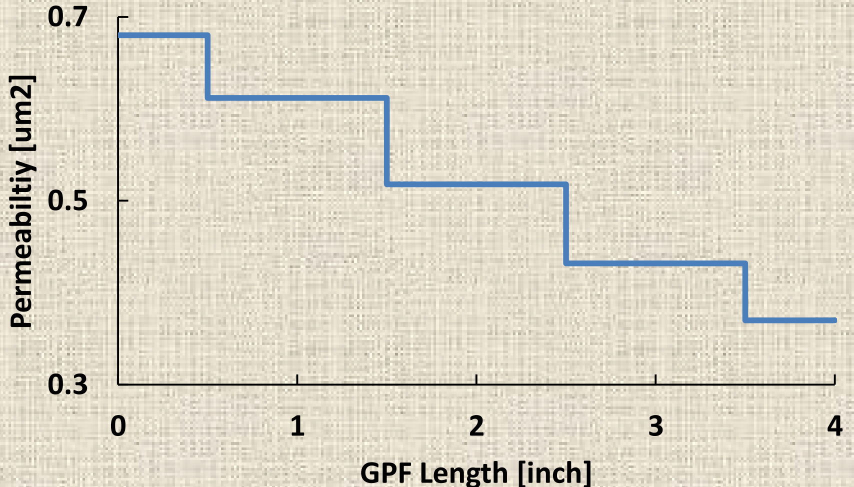


Permeability Changing Axially









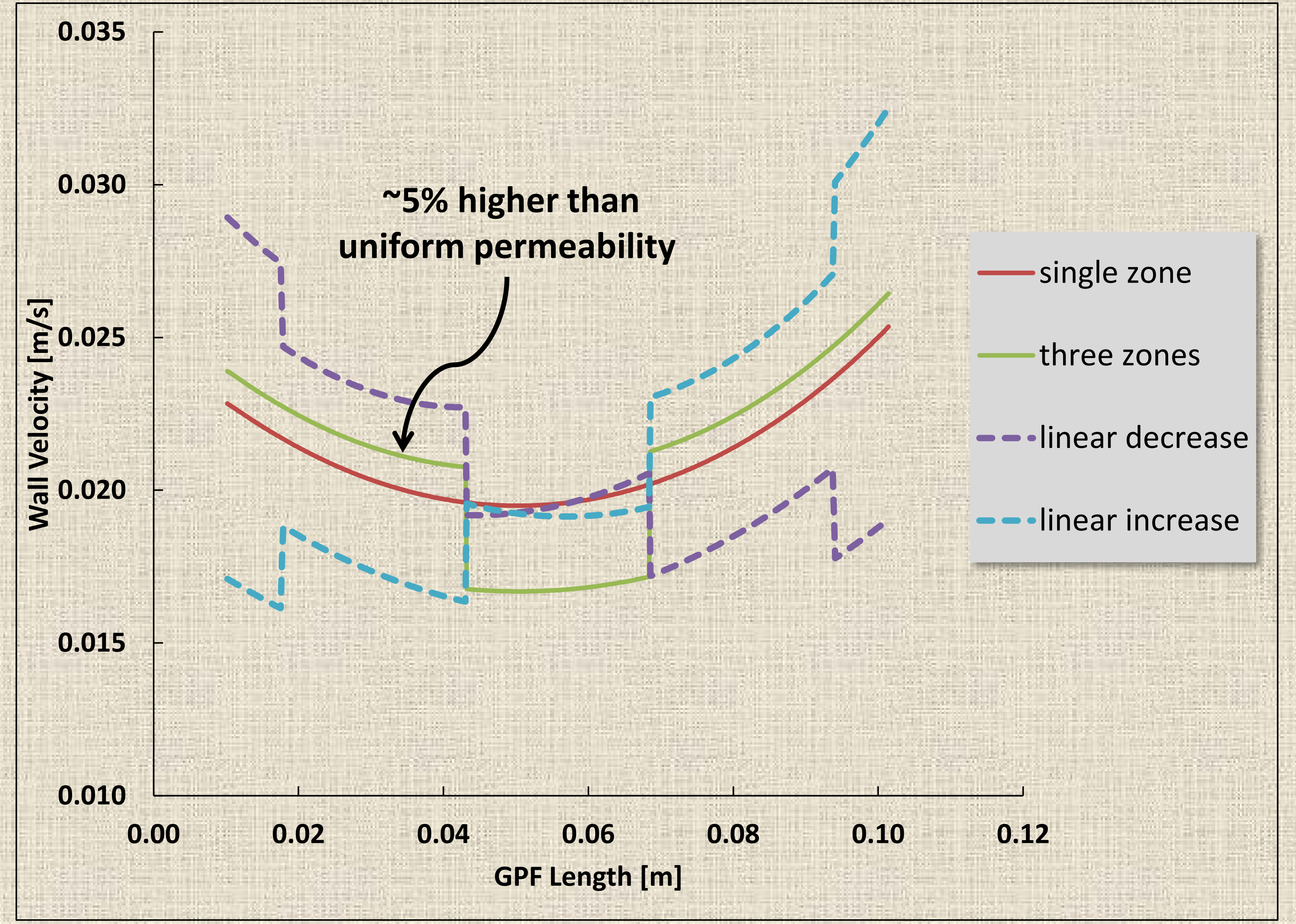
Pressure Drop Comparison

	Pressure Drop	From the Viscous Friction	From the Wall
Uniform	864 Pa	280 Pa	584 Pa
Three Zones	893 Pa	280 Pa	613 Pa
Linearly Increases	830 Pa	280 Pa	550 Pa
Linearly Decreases	830 Pa	280 Pa	550 Pa
1D Analytical from Ford	973 Pa	400 Pa	573 Pa

Three zones has a higher pressure drop due to higher wall velocity

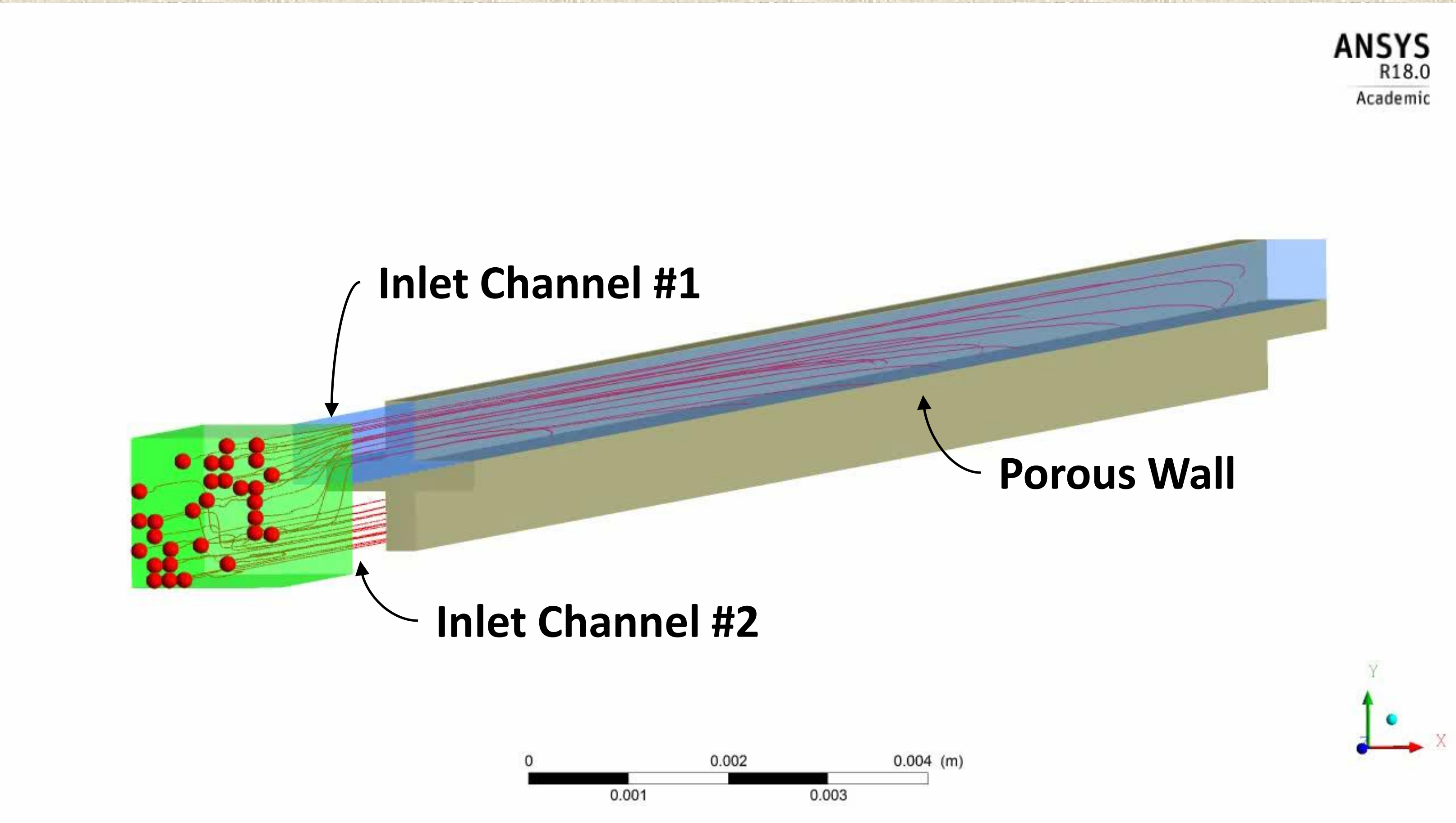
Compared to the 3D prediction, 1D model has a higher pressure drop because of the higher viscous friction

Wall Velocity Comparison

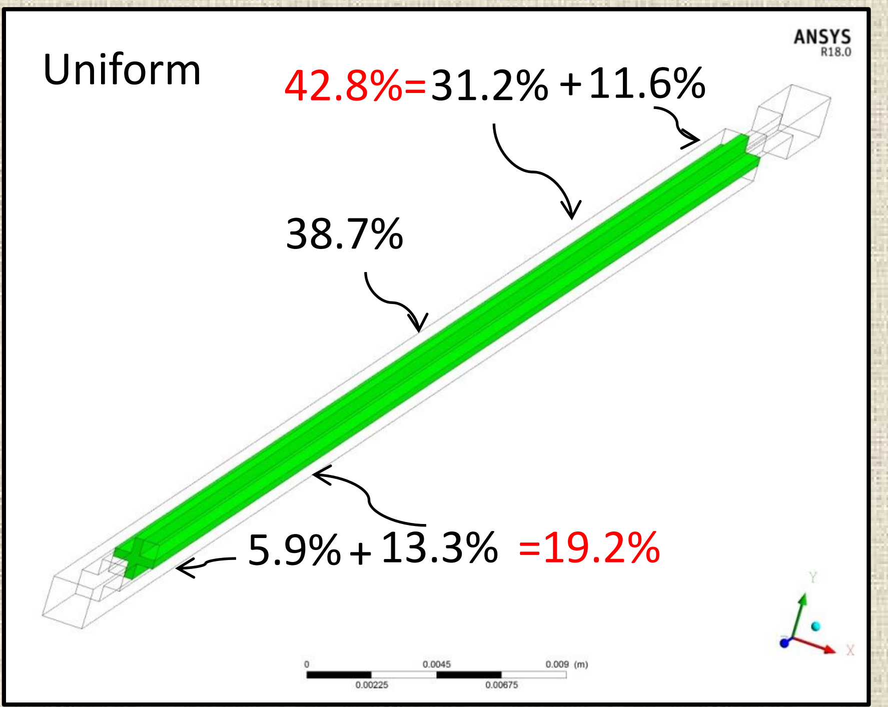


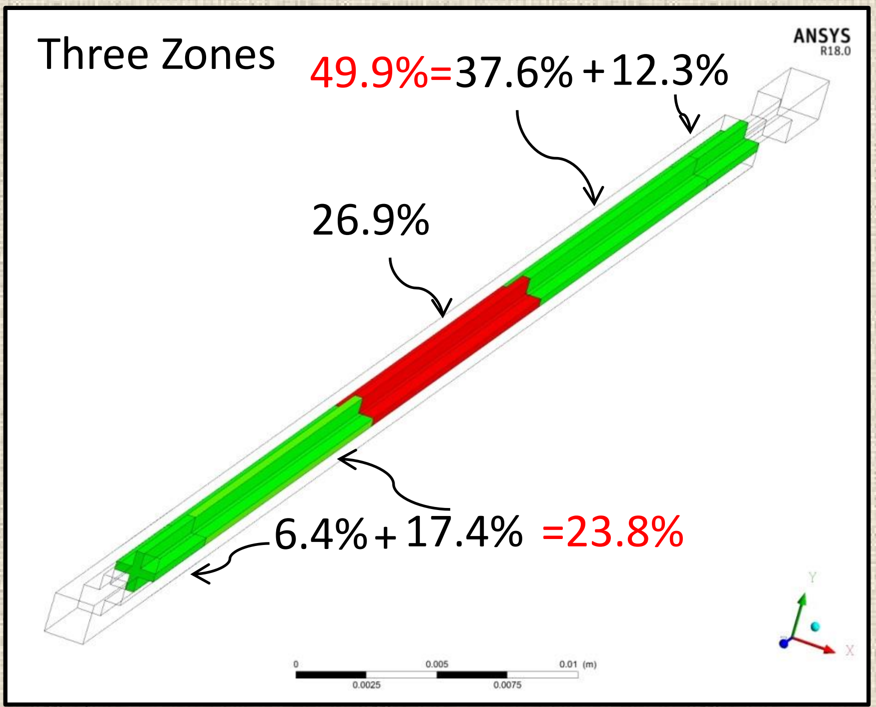
Determining Filtration Efficiency

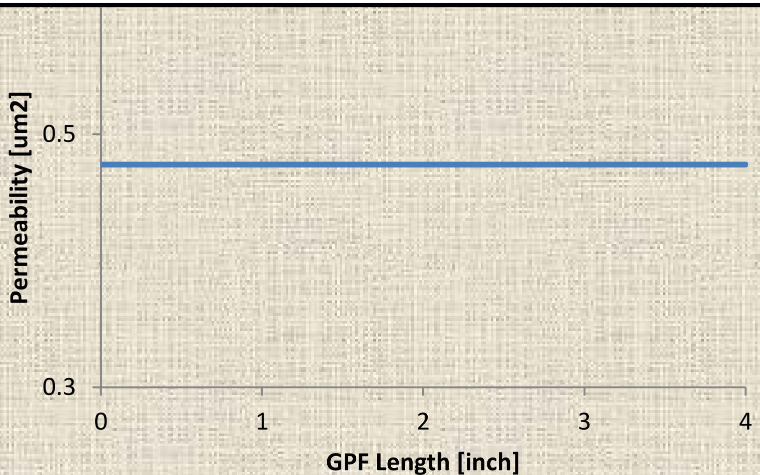
By using User Defined Function (UDF), filtration efficiency can be resolved to every single particle injected in the system, in accordance to their travel speed and local fluid velocity.

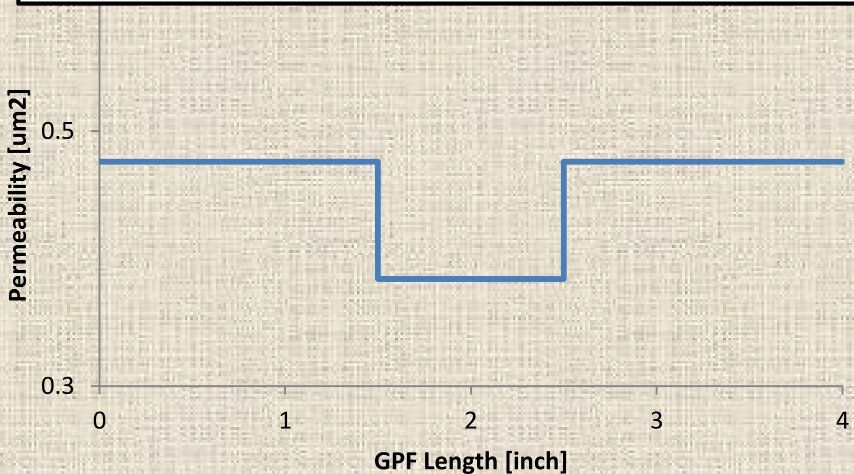


Particle Tracking









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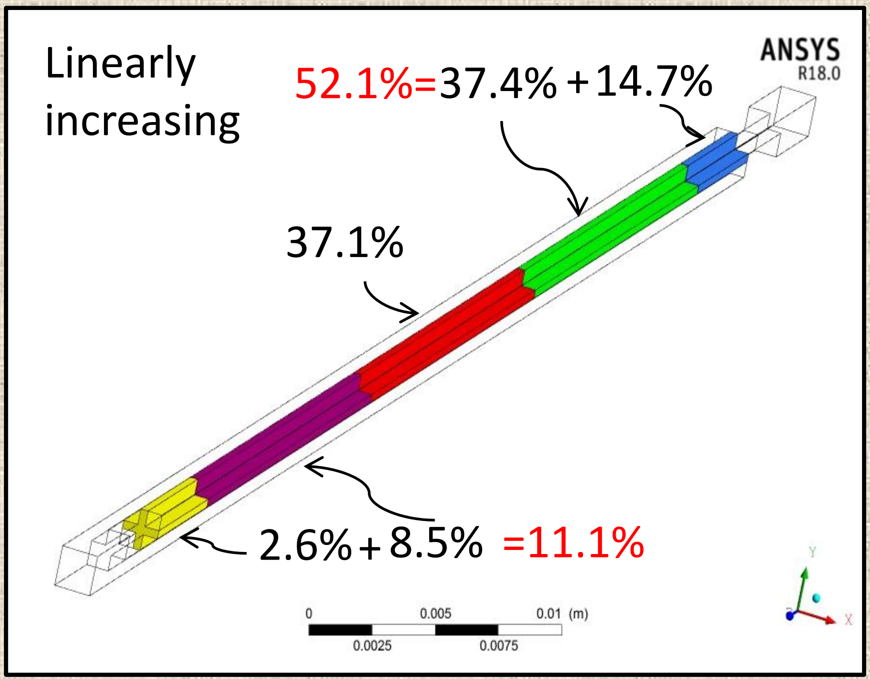

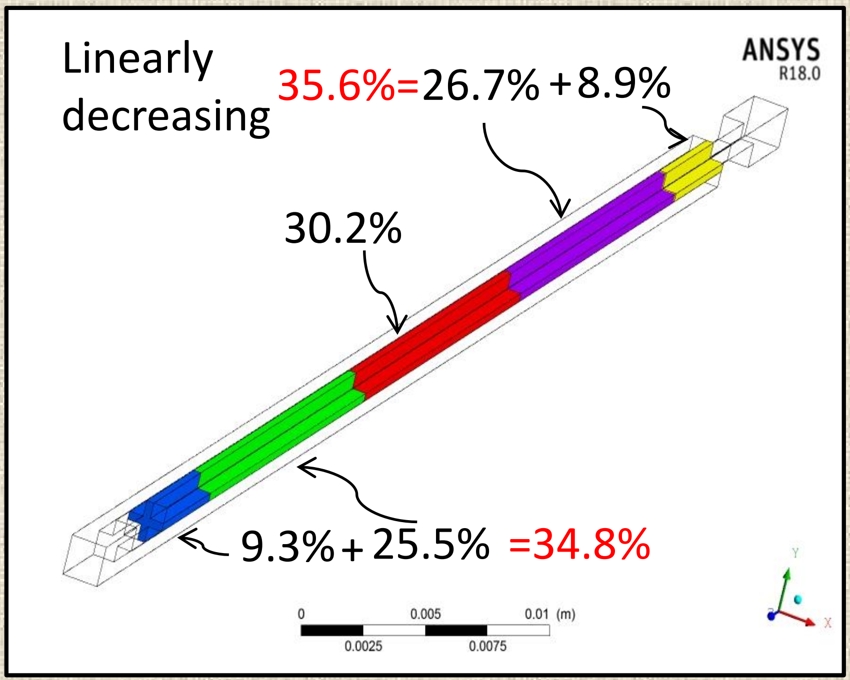

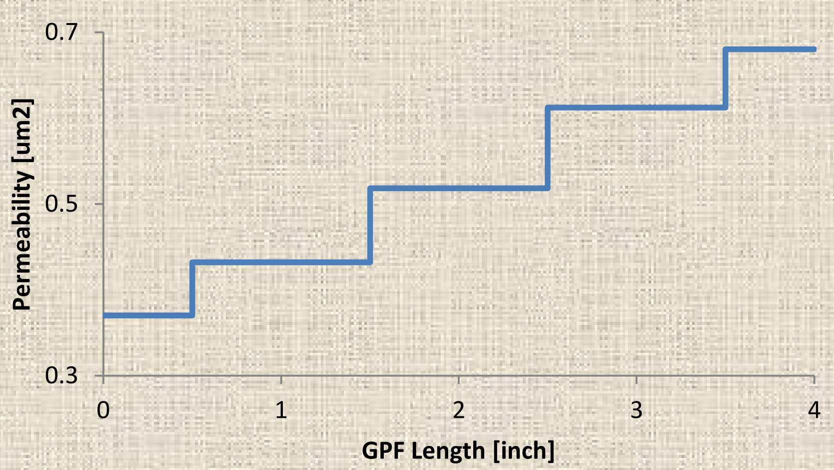

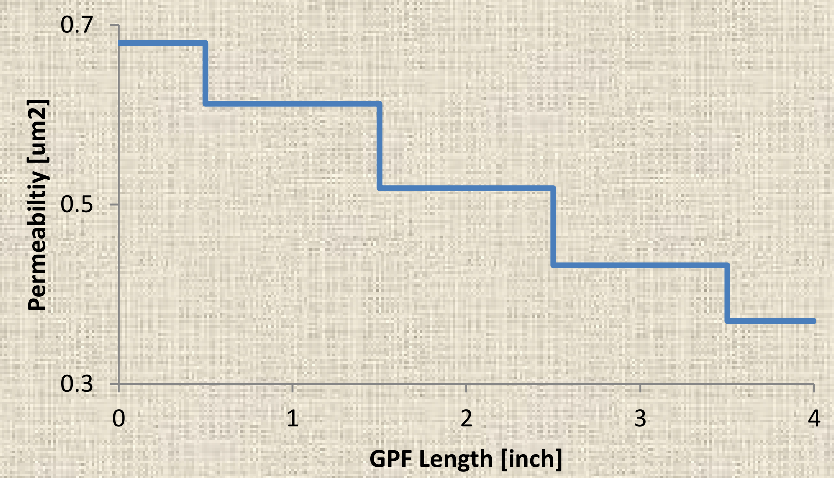

Summary

1. Pore size and distribution study
   - Under the same working condition (500 C, 60 kg/s), a tight pore distribution has a 20% lower pressure drop across the porous wall.
   - However tight pore distribution has a filtration efficiency 25% lower than wide.
2. Pore structure study
   - Using the throat unit collector model, filtration efficiency increases with decreasing diameter ratio.
   - The pressure drop for throat unit collector decreases with decreasing diameter ratio.
3. Permeability uniformity study
   - For most permeability distributions, particles tend to accumulate at the end of channel due to inertial effects.
   - linearly decreasing permeability along the flow path is more stable, with lower overall pressure drop and more even ash storage potential.

Work In Progress

- The effect of the vertical gap between unit collectors is also being investigated.

- Sensitivity study on the influence of average pore size change – *i.e.* wider distribution with smaller average pore size vs. smaller distribution with larger average pore size.

- Develop a method to relate the single unit collector efficiency to total filter efficiency, and compare it with the spherical unit collector model and experiments. $\eta \xrightarrow{?} E(\eta, \varepsilon, w, d_p)$

- Transient study to investigate the permeability uniformity effects on GPF pressure drop, filtration efficiency and ash storage in a longer term.

Acknowledgements

My sincere gratitude goes to the team at Ford Motor Company : Christine Lambert, Jeong Kim, Xin Liu and Jim Pakko for their support and my internship.

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Thank you!

Questions?