

American Society for Gravitational and Space Research Conference, San Juan, Puerto Rico, December 3-7, 2024



Phase Separation with a Porous Screen in Zero Gravity: CFD Modeling and Validation

Rebecca L. Winter¹, Mohammad Kassemi¹

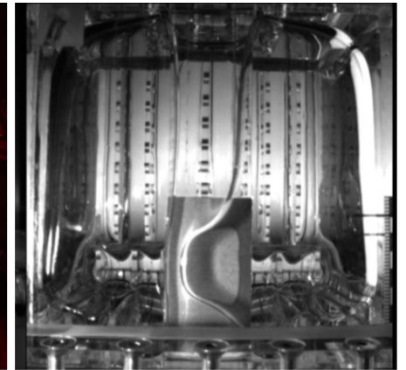
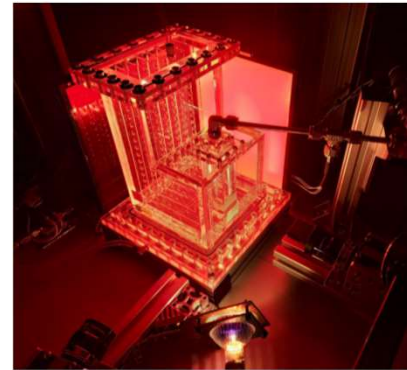
¹ Case Western Reserve University
National Center for Space Exploration Research
NASA Glenn Research Center

December 6, 2024

Zero-Boil-Off Tank Experiment – Filling & Transfer ZBOT-FT (TREX)

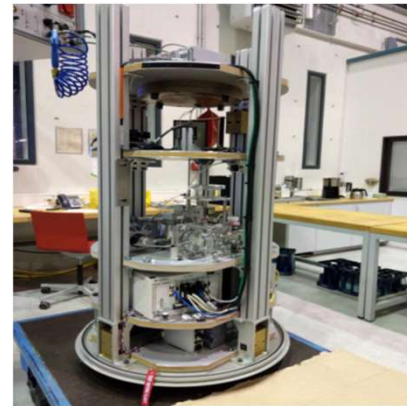
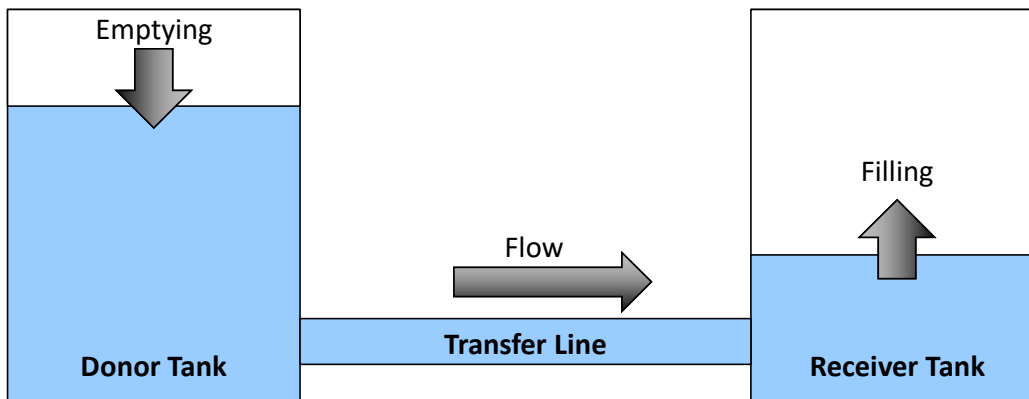


- ZBOT-FT (Filling & Transfer) is a collaboration between NASA/Case Western Reserve University and DLR (German Aerospace Center)/University of Bremen
- The project is designed to study how cryogenic or cryo-simulant fluid behaves when filling, transferring, and emptying a tank in microgravity
- Application for in-flight storage and refueling of cryogenic liquid propellant

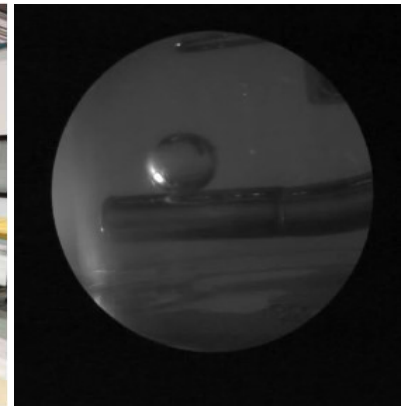


LAD performance tests in Donor Tank

Key Components of the System:



Receiver Tank in Drop Tower Assembly for tank filling tests

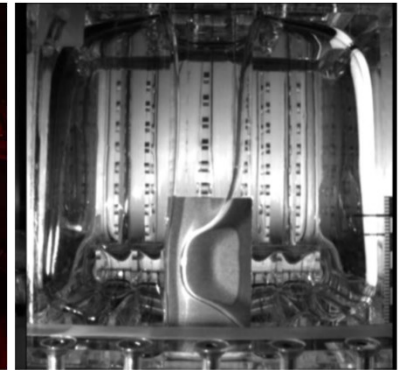
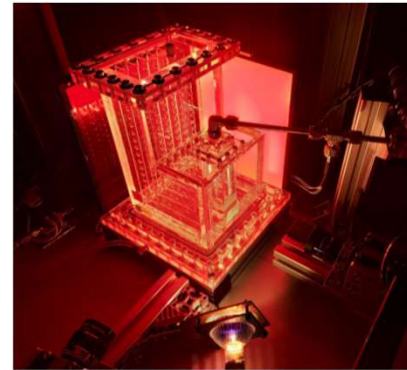


Drop Tower pool cavitation tests with LCH₄

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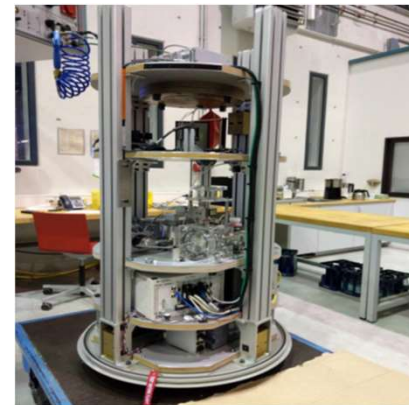
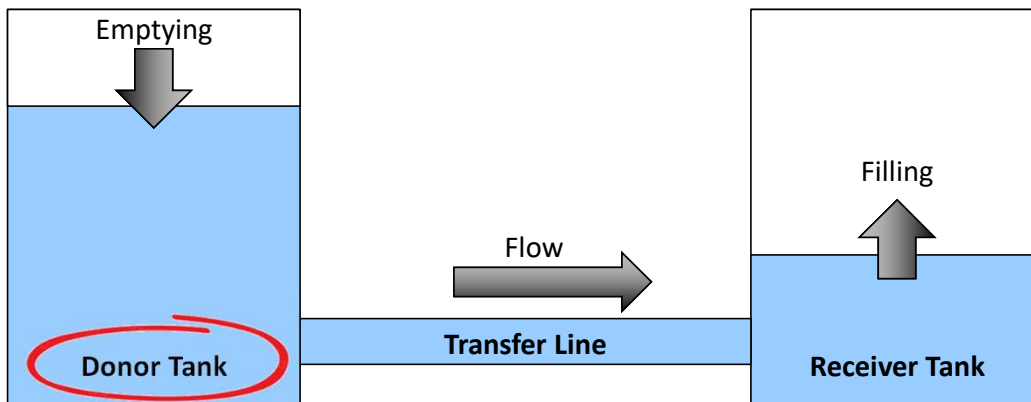


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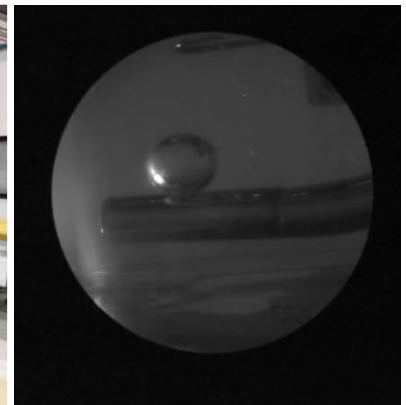


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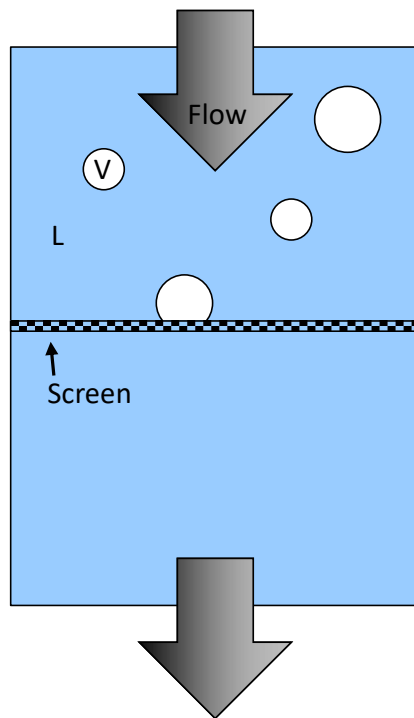


Drop Tower pool cavitation tests with LCH₄

Liquid Acquisition Devices (LADs)

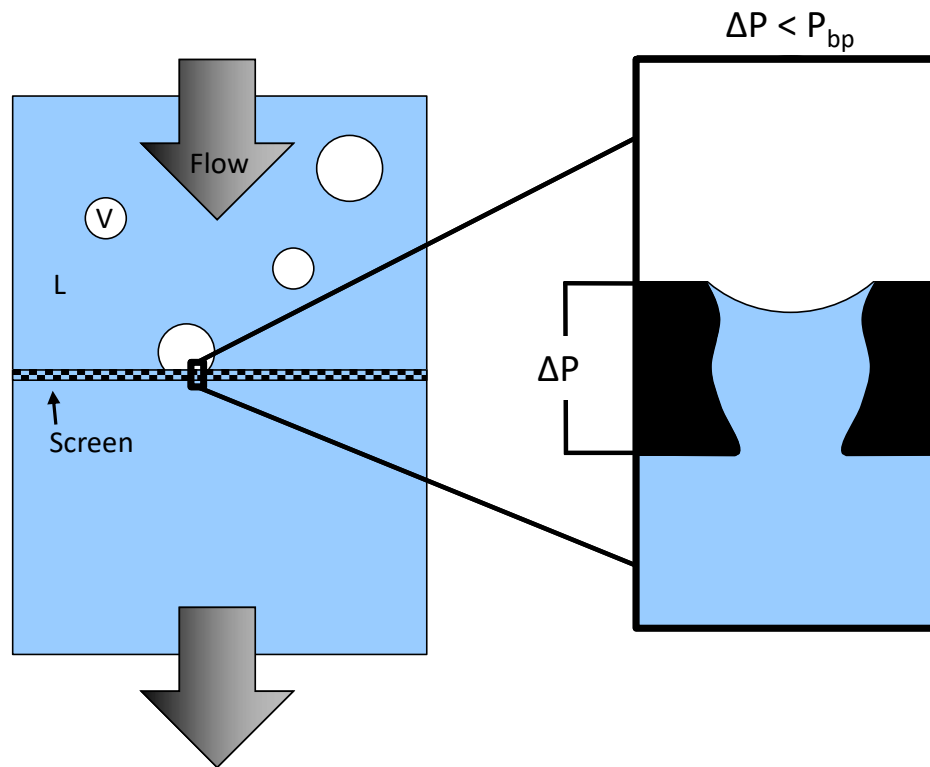


- Screens can be used to prevent vapor bubbles from passing through
- Surface tension in the screen inhibits dryout



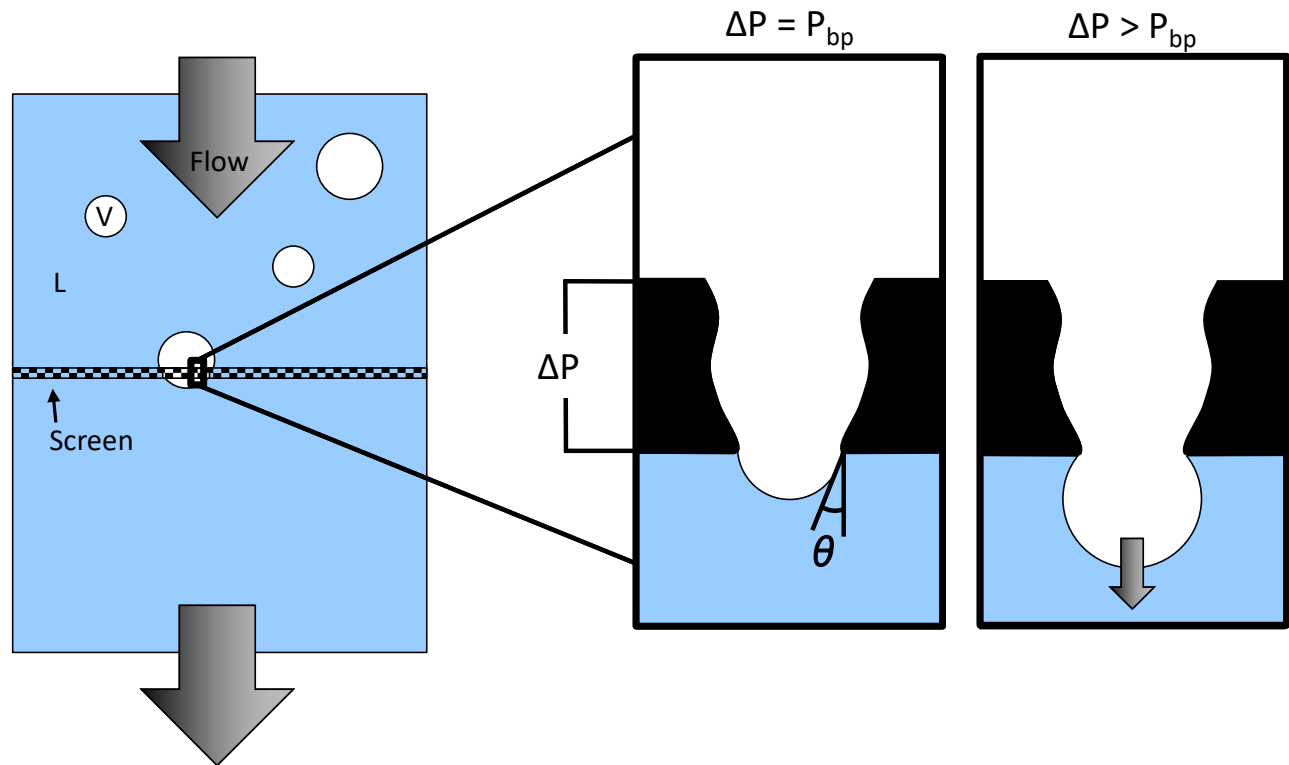
Liquid Acquisition Devices (LADs)

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Liquid Acquisition Devices (LADs)

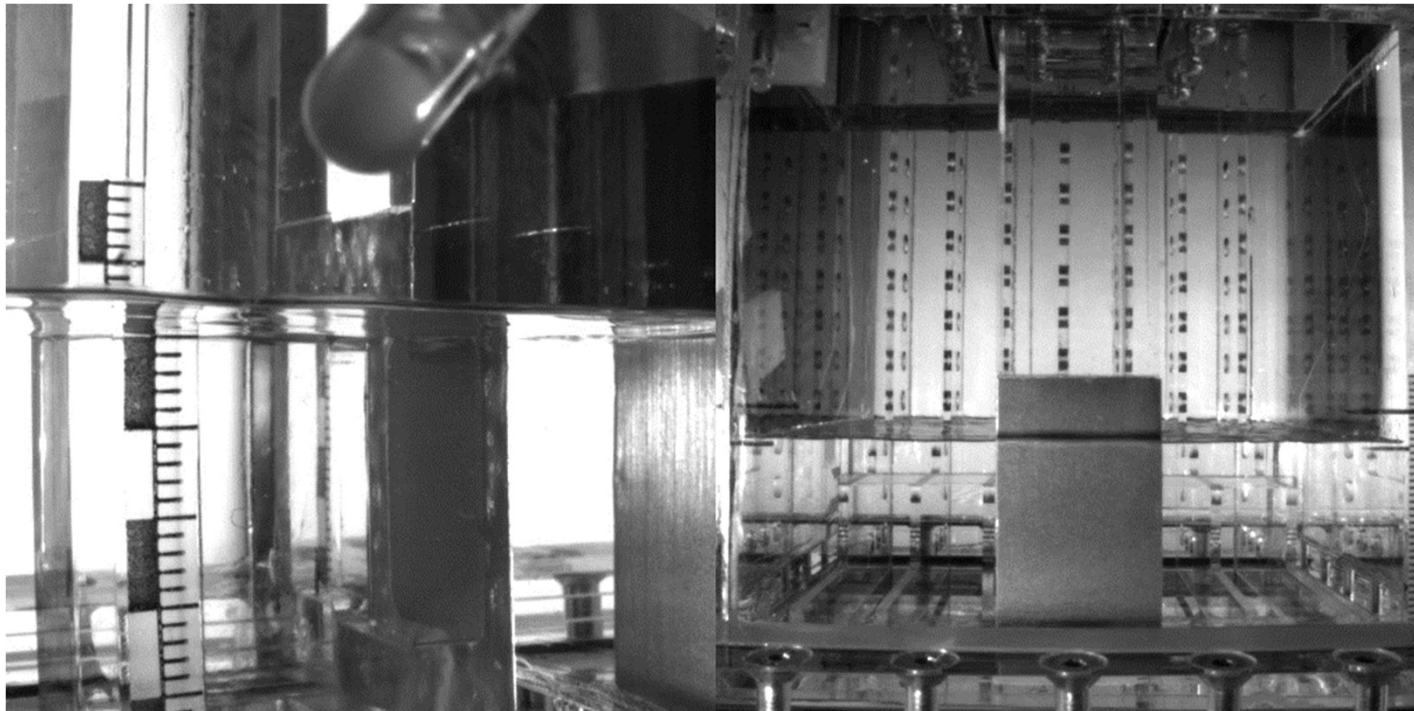
- Screens can be used to prevent vapor bubbles from passing through
- Surface tension in the screen inhibits dryout
- Bubbles can pass through the screen once a critical pressure is reached (bubble point pressure)



Bremen Experiment



Drop tower experiment performed at University of Bremen [Shukla & Dreyer 2024]



Motivation and Goal



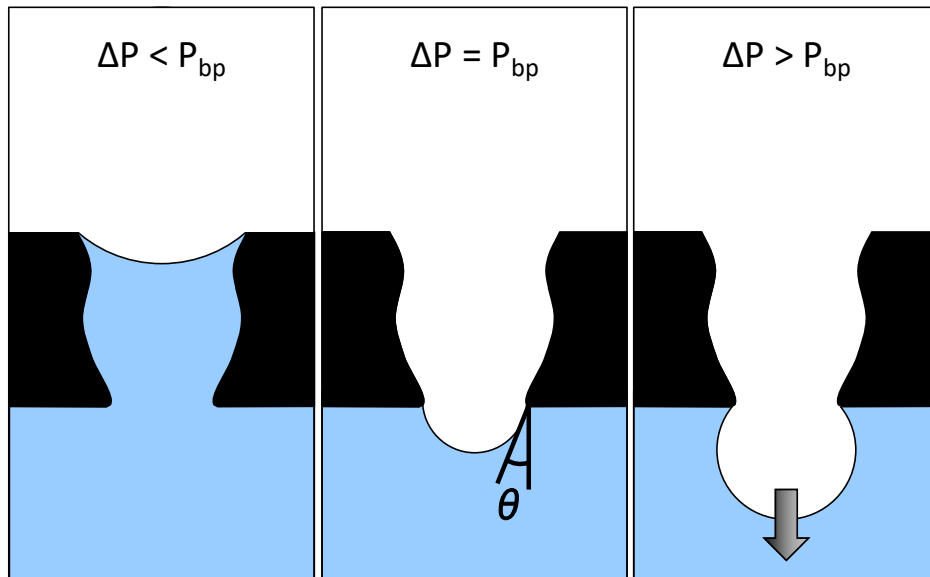
- Motivation for studying screen Liquid Acquisition Device (LAD)
 - Bubbles entering the transfer line could negatively impact the refueling operation
 - Screen LADs use surface tension to prevent bubbles from passing through below a critical pressure
- **The goal is to develop a model for studying the behavior of a screen Liquid Acquisition Device (LAD) in zero gravity**
- Summary of Talk
 - ✓ Overview of Screen Liquid Acquisition Devices (LADs)
 - Bubble Point Pressure
 - Dynamic Pressure Drop
 - Preliminary Modeling of Full Tank

Static Bubble Point Theory

Young Laplace Equation: $\Delta P = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$

Jason Hartwig 2015; Conrath and Dreyer 2012:

$$\Delta P_{bp} = \frac{2 \sigma \cos(\theta)}{R_{bp}} = C_0 \frac{4 \sigma \cos(\theta)}{D_p} = 1862.46 \text{ Pa}$$



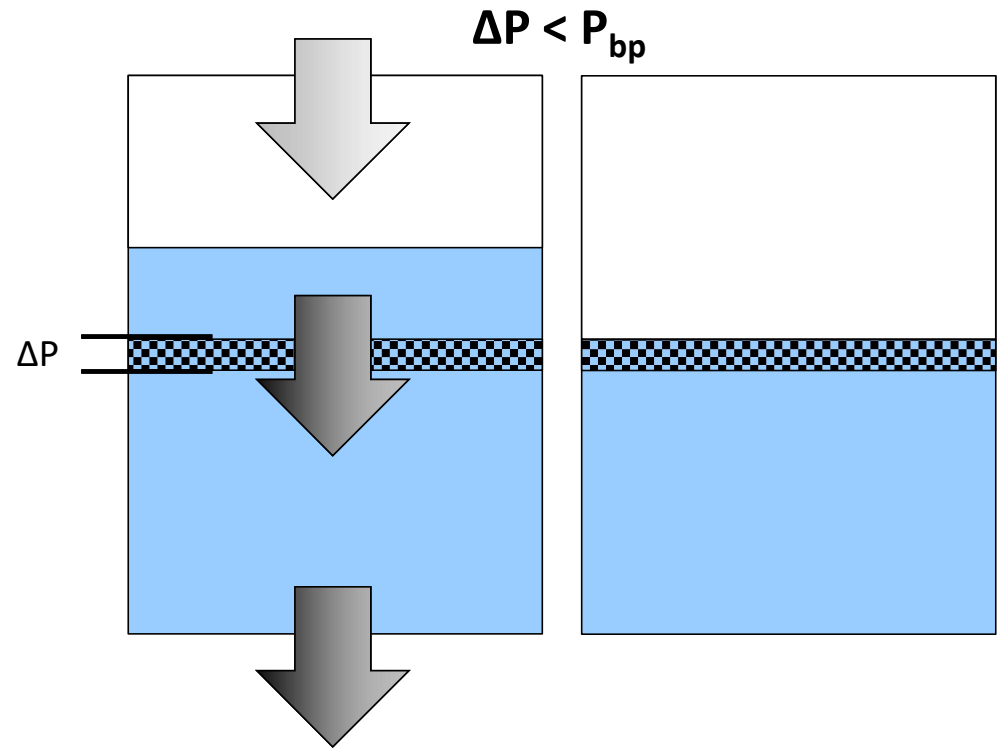
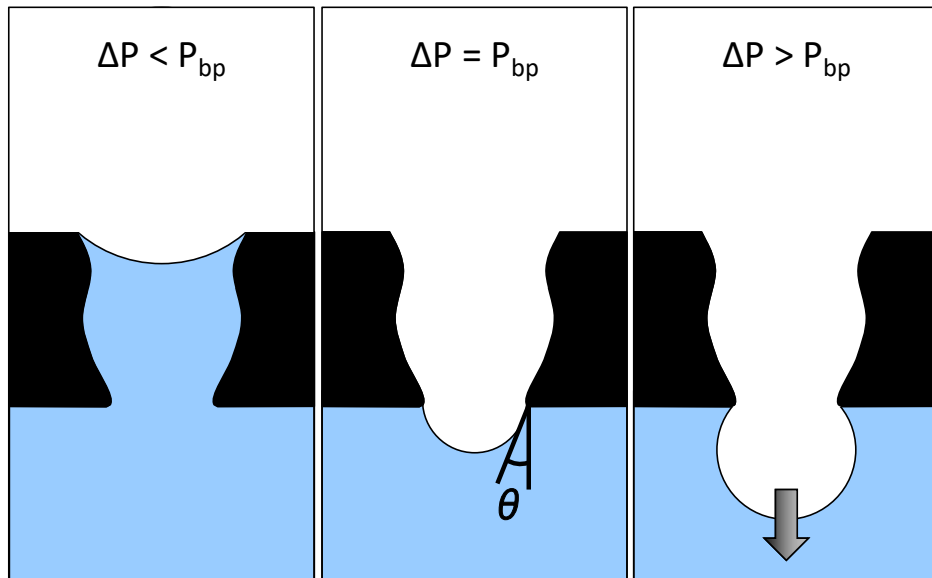
Hartwig, J. W. (2015). *Liquid acquisition devices for advanced in-space cryogenic propulsion systems*. Academic Press.
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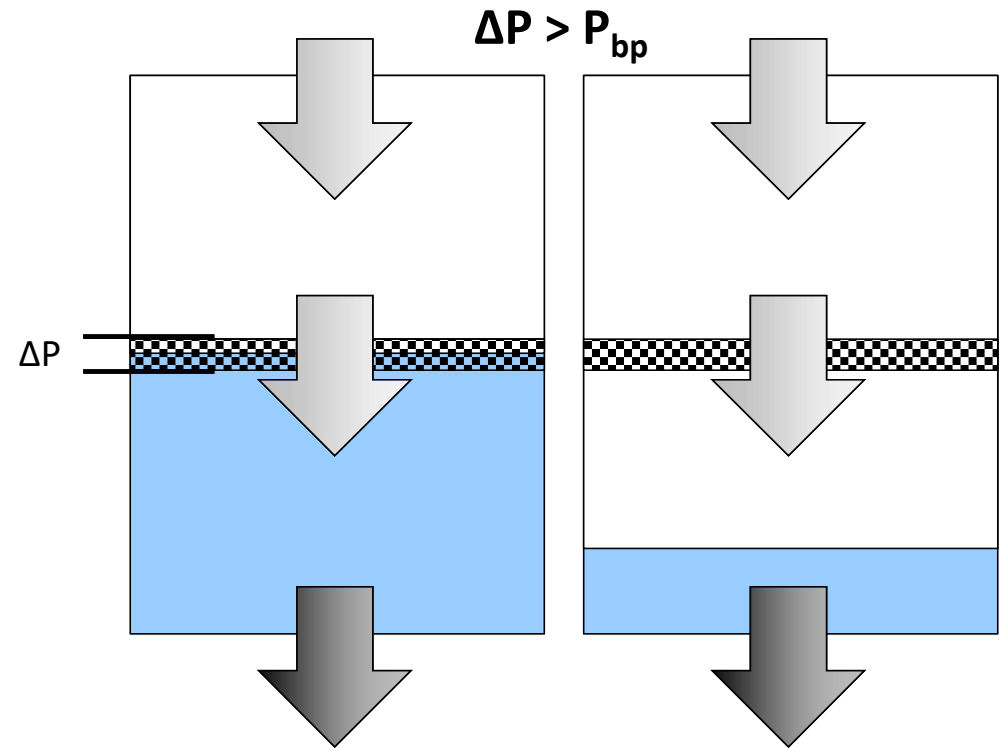
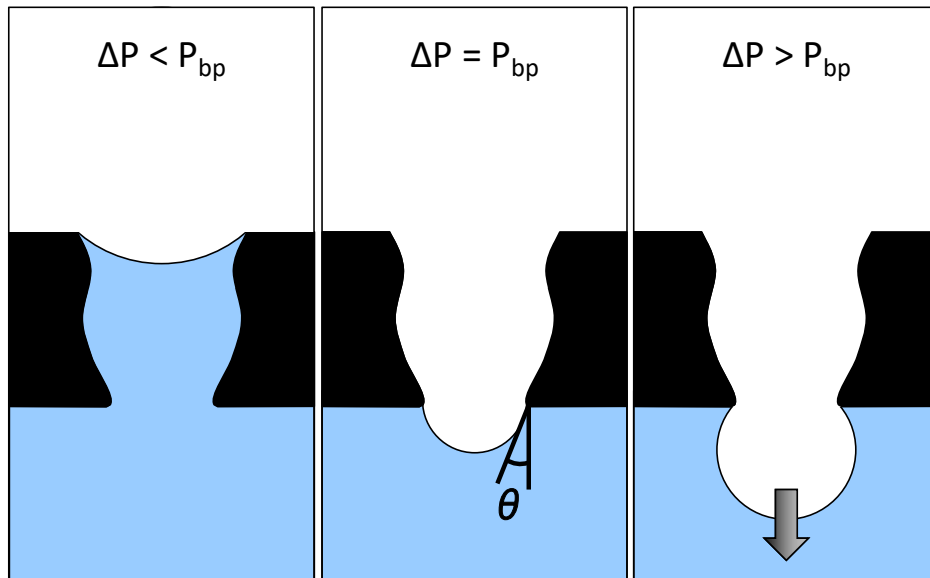
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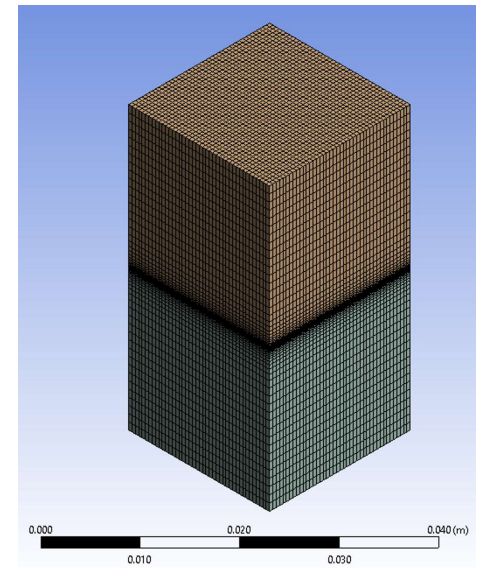
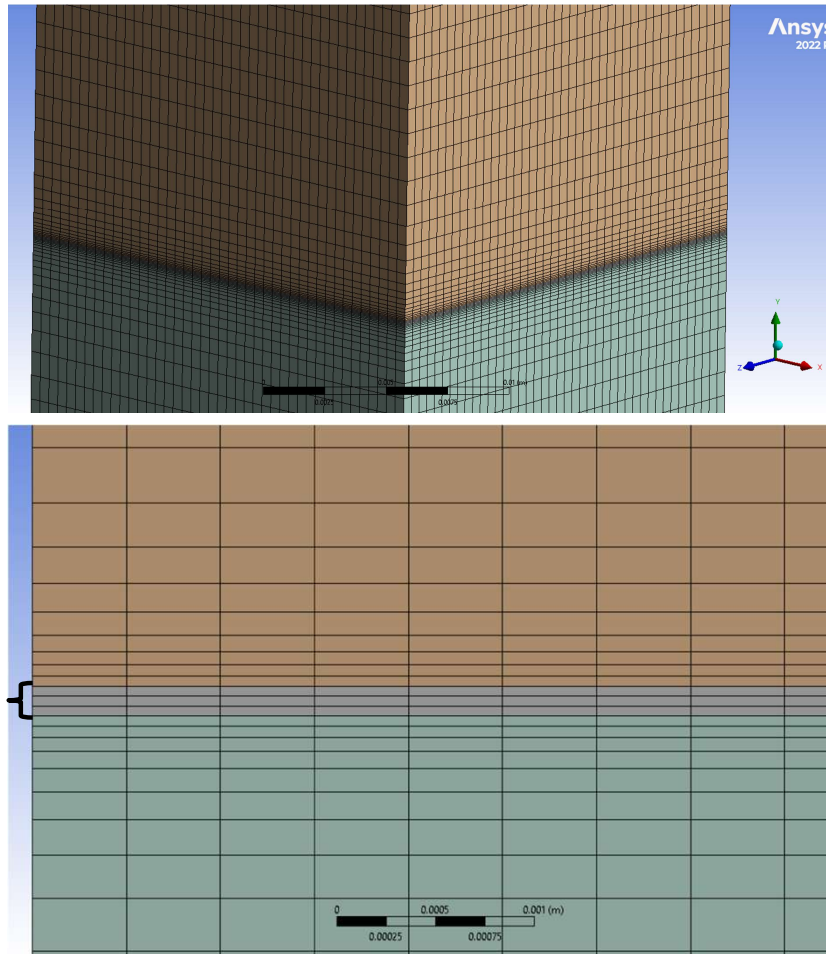


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Setup for Static Bubble Point Case



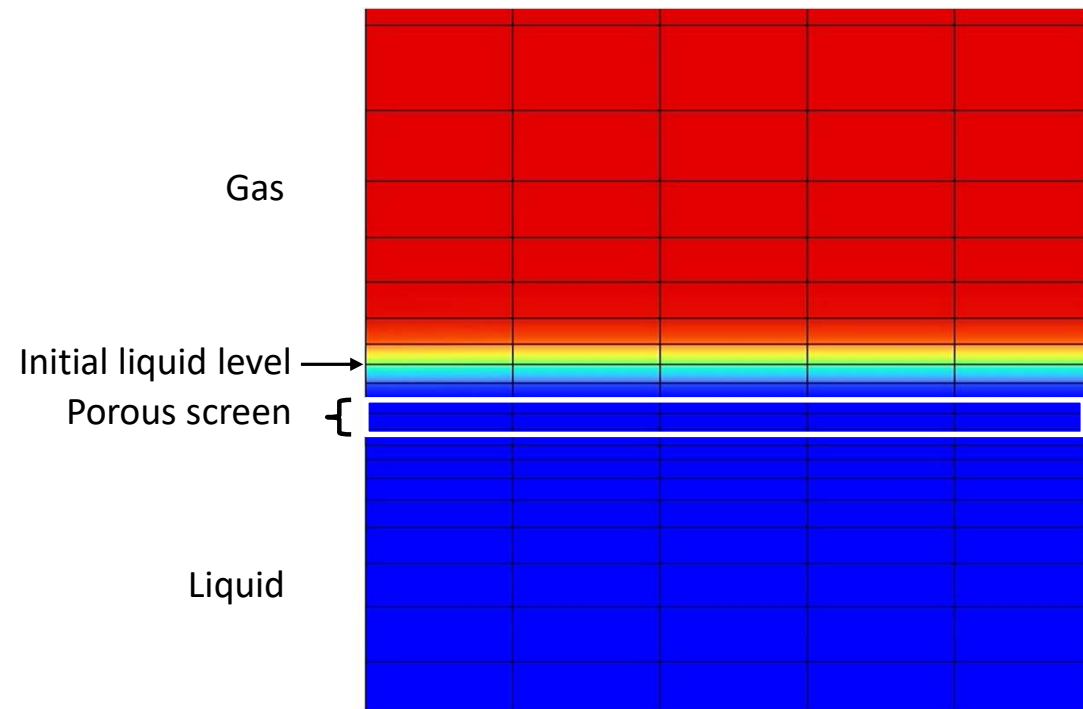
- Mesh has 111,132 elements
- 3 cells across the thickness of the porous screen
- All hexagonal elements, finer near porous screen
- No phase change

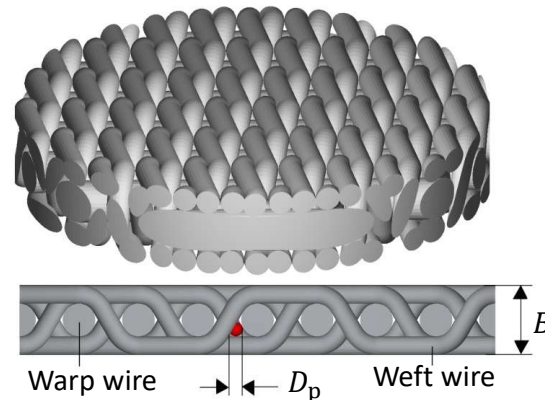


Setup for Static Bubble Point Case



- Boundary Conditions
 - No slip walls around
 - Pressure inlet top (linearly increasing slope, gas in)
 - Pressure outlet bottom (constant, liquid backflow)
- Initial Conditions
 - Liquid from bottom to 200 μm above porous zone
 - Gas above
 - Entire domain 86303 Pa





Screen Properties of DTW 200x1400:

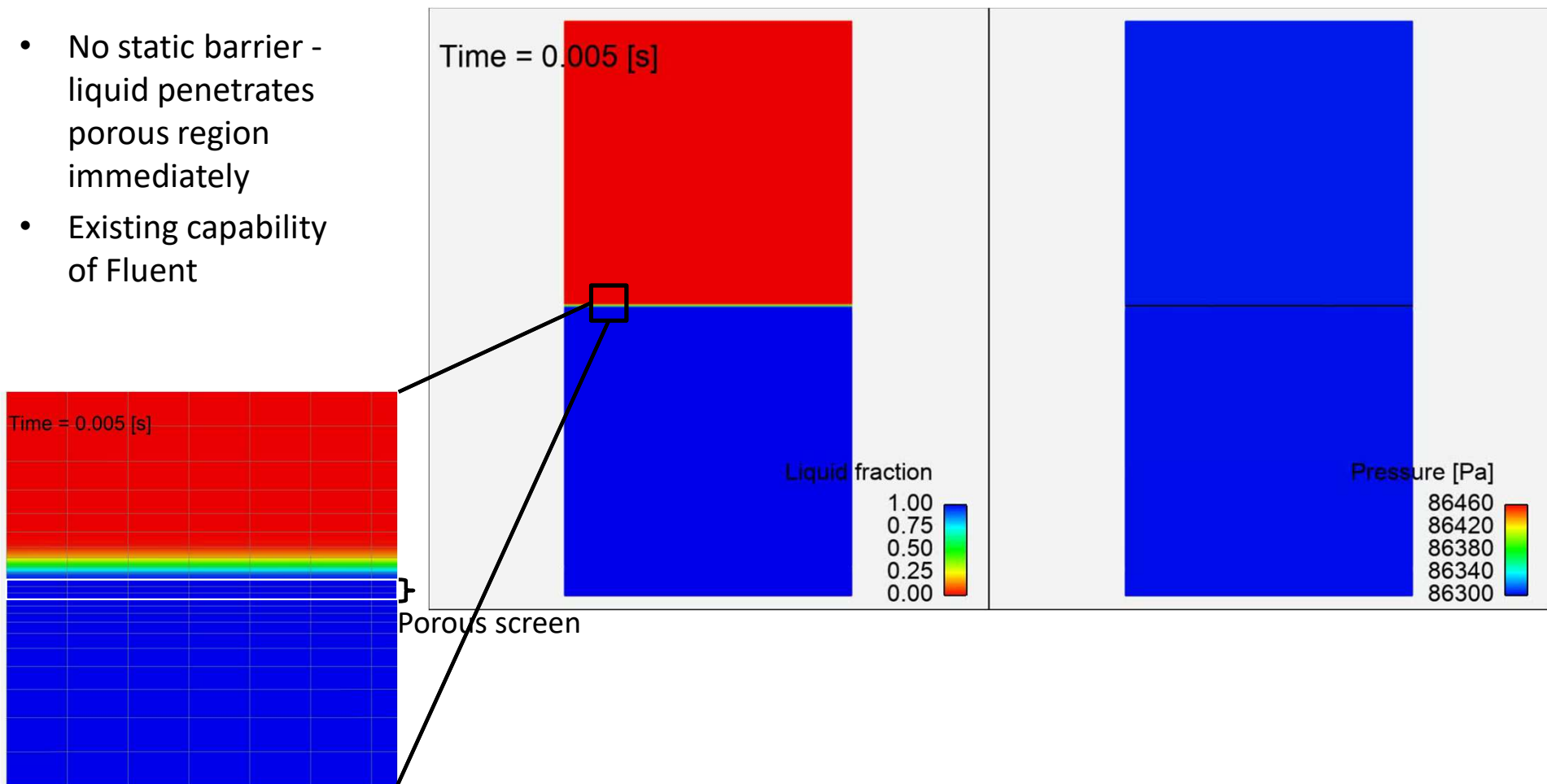
Screen thickness:	$B = 150 \mu\text{m}$
Mean average porosity:	$\bar{\phi} = (0.28 \pm 0.05)$
Particle retention diameter:	$D_p = (13 \pm 1) \mu\text{m}$
Tortuosity:	$\tau = 1.28$
Surface area to volume ratio:	$S = 0.062 \mu\text{m}^{-1}$
Viscous pressure loss coefficient:	$C_2 = 0.33$
Inertial pressure loss coefficient:	$C_1 = 5.61$
Warp wire diameter:	$D_{\text{warp}} = 70 \mu\text{m}$
Weft wire diameter:	$D_{\text{weft}} = 40 \mu\text{m}$
Mean averaged bubble point diameter:	$\overline{D}_{\text{bp}} = (20.14 \pm 2.14) \mu\text{m}$

Fluid Properties of Perfluoropentane (PNP, C_5F_{12}):

Saturation pressure:	$P_{\text{sat}} = 86303 \text{ Pa}$
Saturation temperature:	$T_{\text{sat}} = 298.15 \text{ K}$
Liquid density:	$\rho_l = 1604.9 \text{ kg/m}^3$
Gas density:	$\rho_g = 10.6 \text{ kg/m}^3$
Liquid dynamic viscosity:	$\mu_l = 461.6 \mu\text{Pas}$
Gas dynamic viscosity:	$\mu_g = 11 \mu\text{Pas}$
Surface tension:	$\sigma = 9.4 \text{ Nm}$
Liquid thermal conductivity:	$\lambda_l = 64 \text{ W/(m K)}$
Gas thermal conductivity:	$\lambda_g = 11.4 \text{ W/(m K)}$
Liquid specific heat capacity:	$c_{\text{vl}} = 824.9 \text{ J/(kg K)}$
Gas specific heat capacity:	$c_{\text{vg}} = 779.5 \text{ J/(kg K)}$

Animation with No Static Barrier

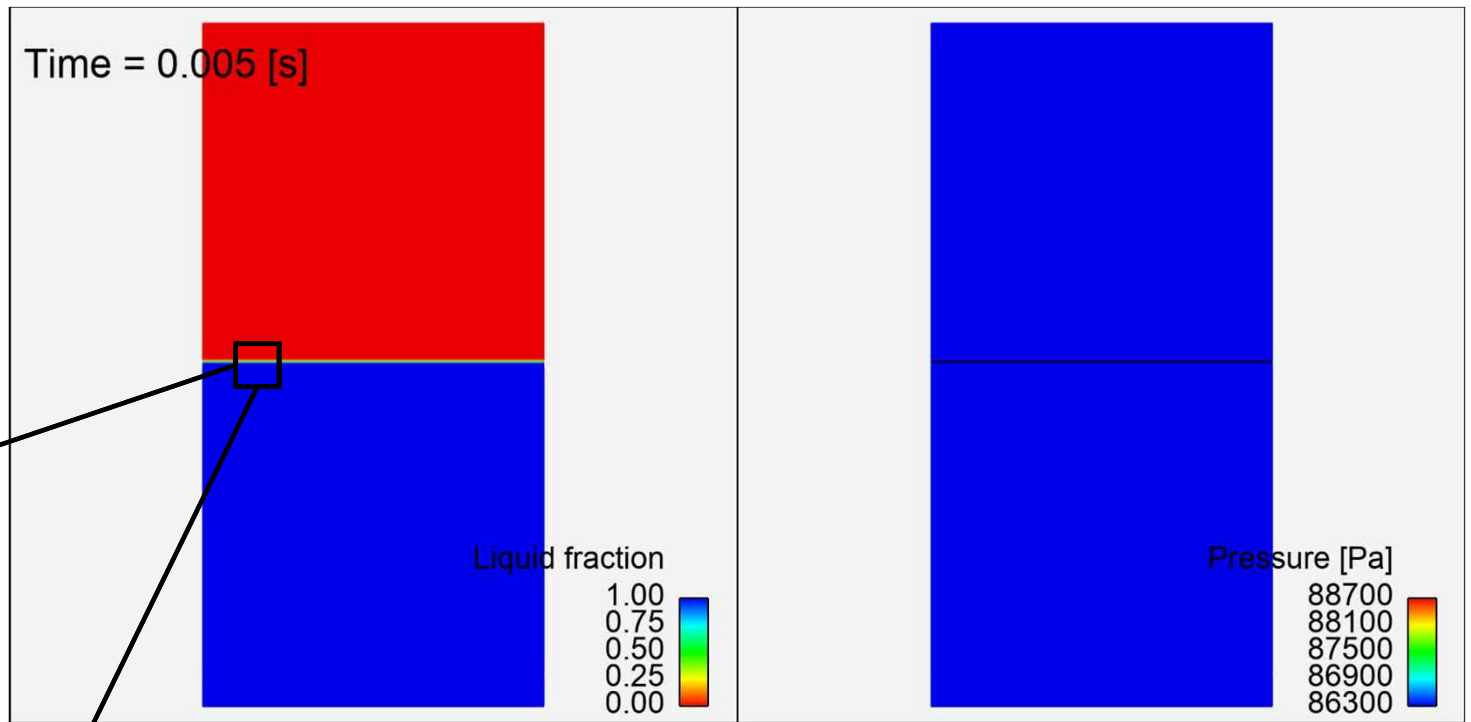
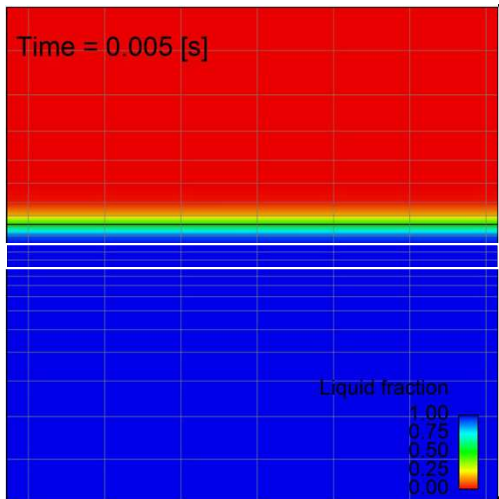
- No static barrier - liquid penetrates porous region immediately
- Existing capability of Fluent





Animation for Static Bubble Point Case

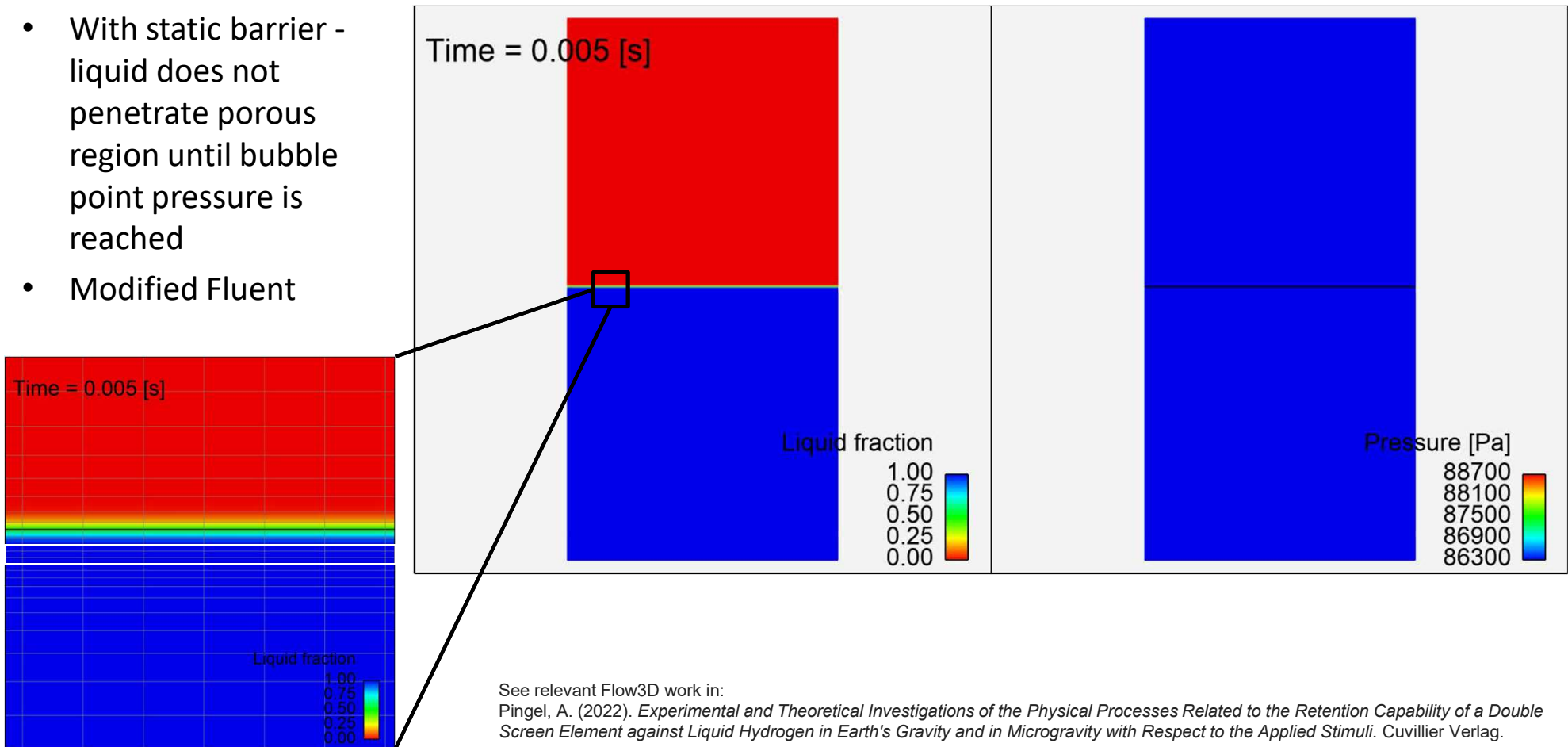
- With static barrier - liquid does not penetrate porous region until bubble point pressure is reached
- Modified Fluent



See relevant Flow3D work in:
Pingel, A. (2022). *Experimental and Theoretical Investigations of the Physical Processes Related to the Retention Capability of a Double Screen Element against Liquid Hydrogen in Earth's Gravity and in Microgravity with Respect to the Applied Stimuli*. Cuvillier Verlag.

Animation for Static Bubble Point Case

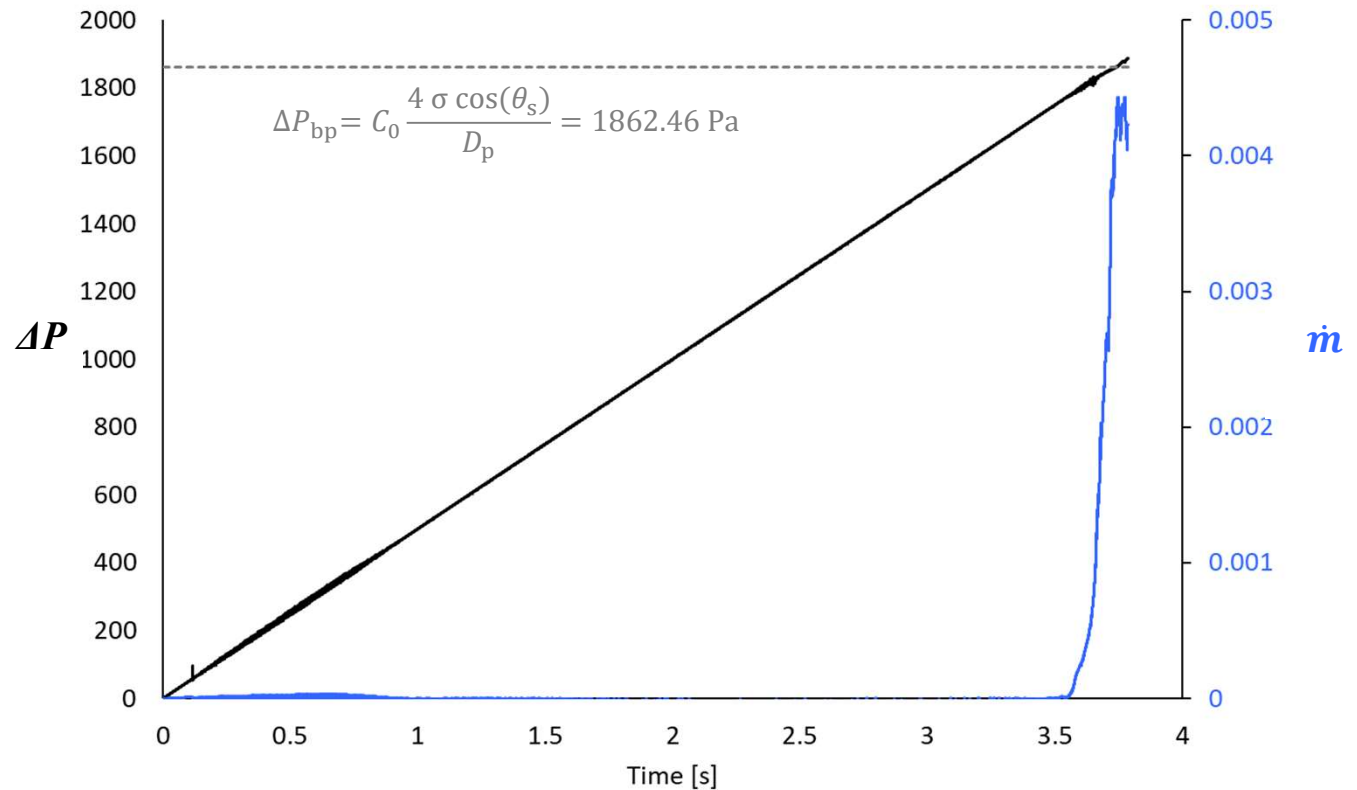
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Compare Static Bubble Point Case to Theory

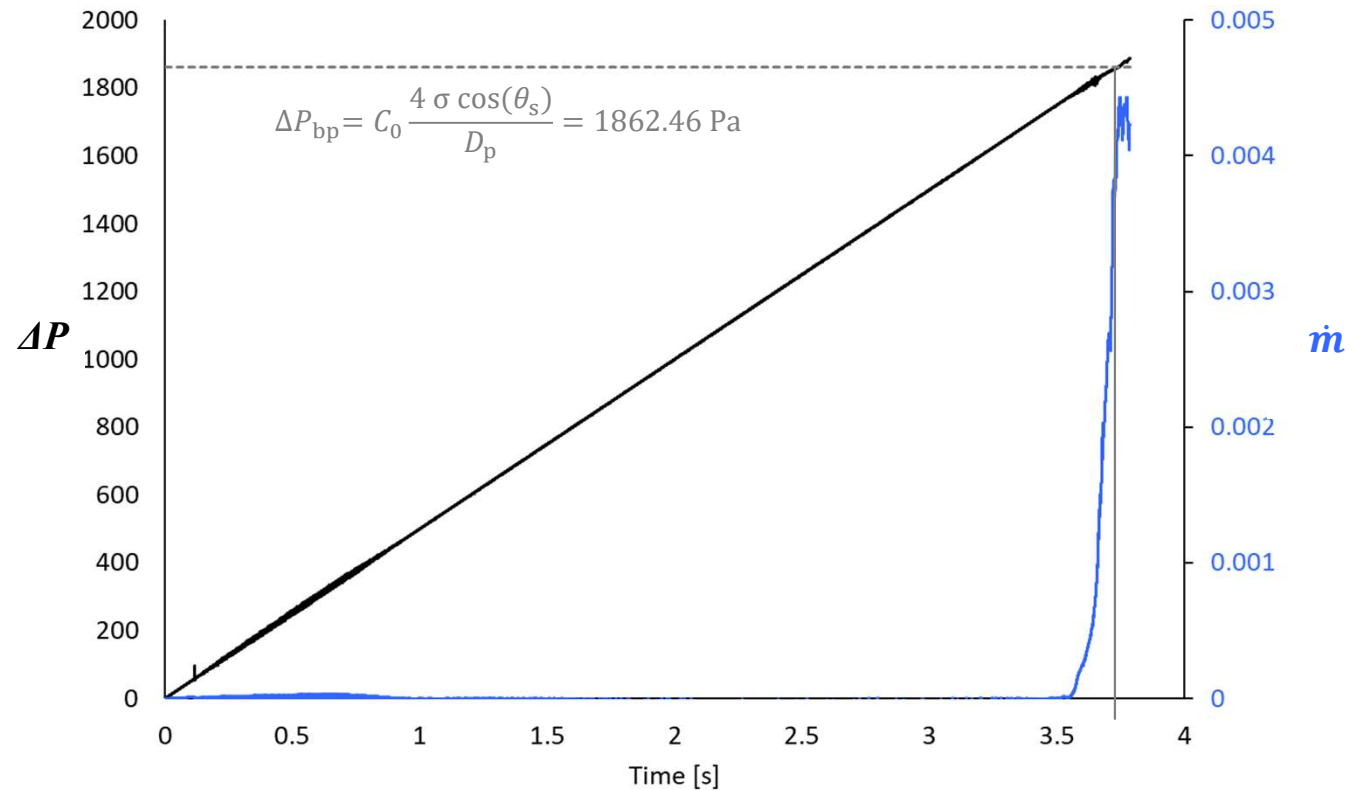
- Gas pushes through screen when bubble point pressure is reached
- Bubble point corresponds to start of large non-zero flow





Compare Static Bubble Point Case to Theory

- Gas pushes through screen when bubble point pressure is reached
- Bubble point corresponds to start of large non-zero flow



Theory for Dynamic All-liquid Case



Pressure difference across the screen
[Armour and Cannon 1968]:

$$\Delta P = \underbrace{\mu B D_y \bar{v}}_{\text{Viscous term}} + \underbrace{\frac{1}{2} \rho B C_y \bar{v}^2}_{\text{Inertial term}}$$

Where:

$$D_y = \frac{C_1 \mu \tau S^2}{\phi^2}$$

$$C_y = \frac{2 C_2 \tau}{\phi^2 D_p}$$

$\bar{v} = \dot{m} / \rho A =$ Velocity

$\mu =$ Liquid viscosity

$\rho =$ Liquid density

$B =$ Screen thickness

$\phi =$ Screen porosity

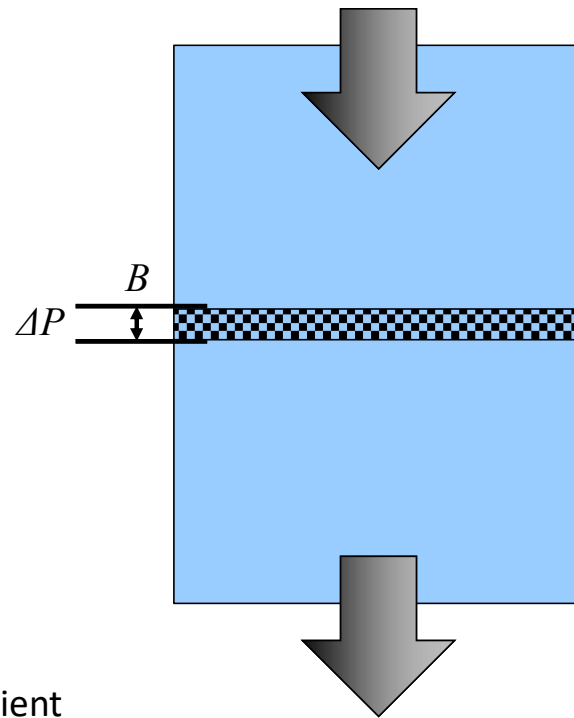
$D_p =$ Particle retention diameter

$\tau =$ Tortuosity

$S =$ Surface area to volume ratio

$C_1 =$ Viscous pressure loss coefficient

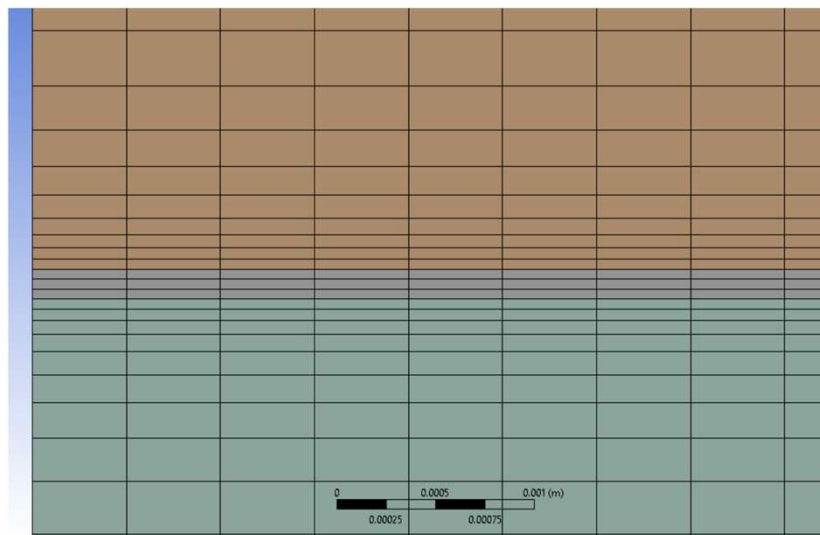
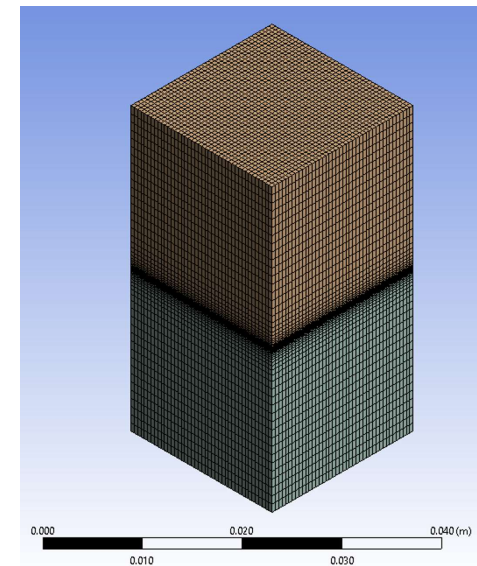
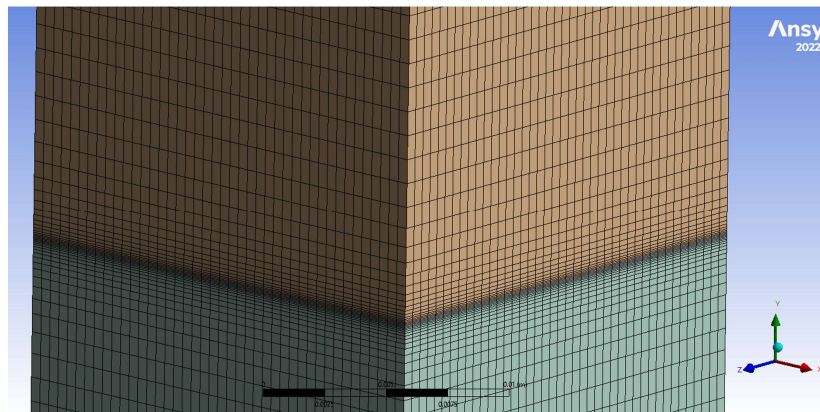
$C_2 =$ Inertial pressure loss coefficient



Setup for Dynamic All-liquid Case



- Mesh has 111,132 elements
- 3 cells across the thickness of the porous screen
- All hexagonal elements, finer near porous screen

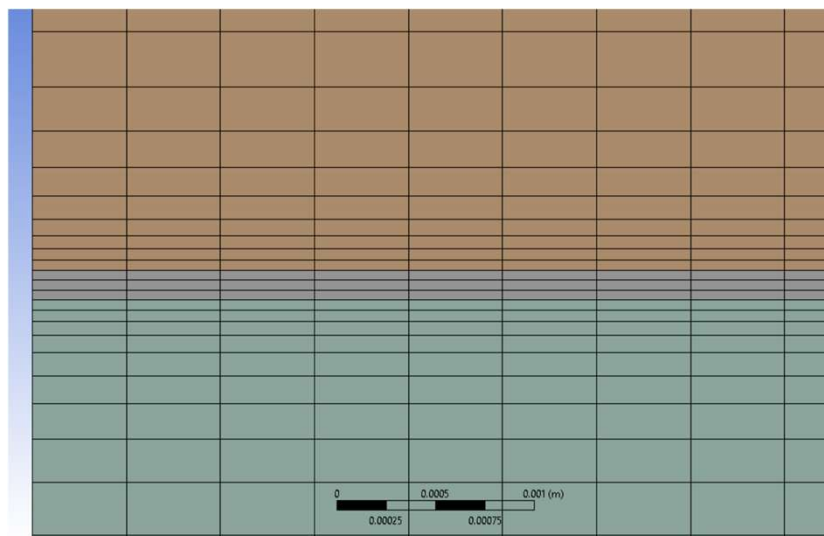
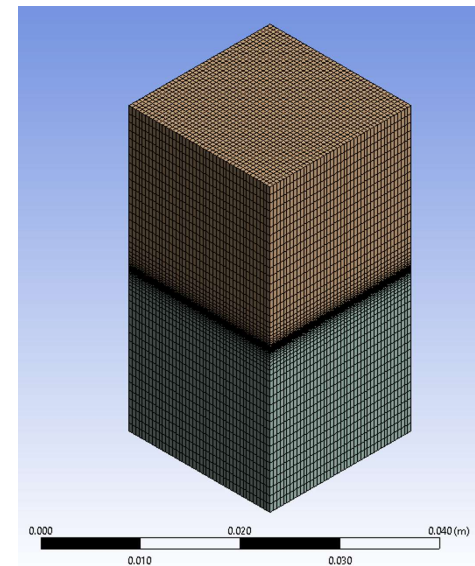
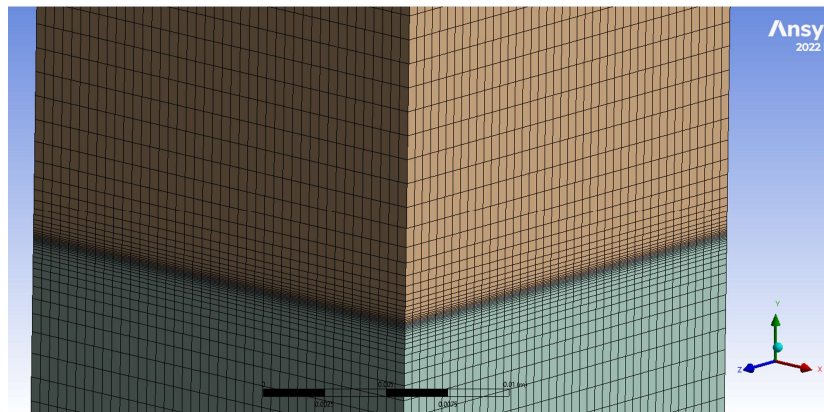


Porous screen

Setup for Dynamic All-liquid Case



- Porous zone at the center
- Boundary Conditions
 - Free slip walls
 - Pressure inlet top (linearly increasing slope, liquid in)
 - Pressure outlet bottom (constant, liquid backflow)
- Initial Conditions
 - All liquid
 - Entire domain 86303 Pa

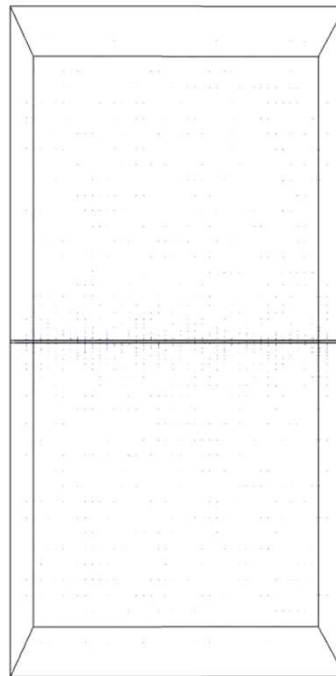
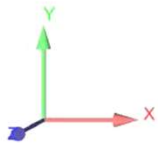


Porous screen

Animation for Dynamic All-liquid Case



Time = 0.05 s



Velocity [m/s]

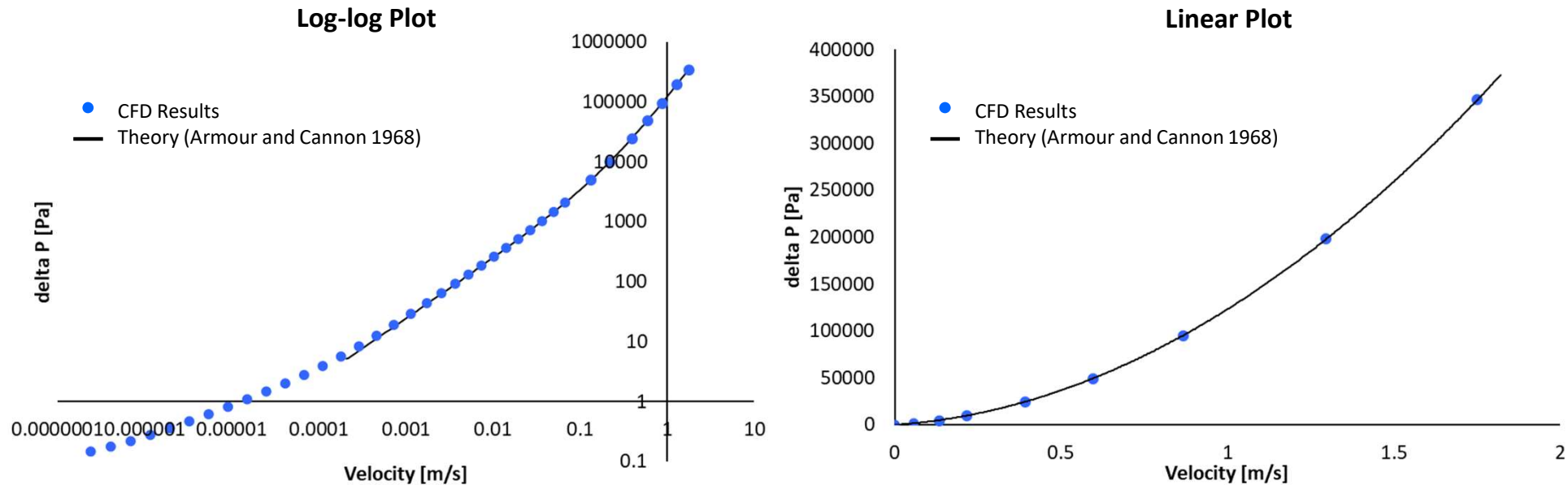
0.0900
0.0675
0.0450
0.0225
0.0000



Compare Dynamic All-liquid Case to Theory



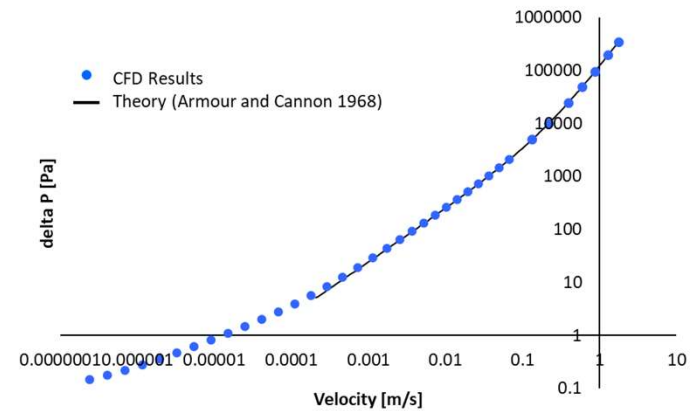
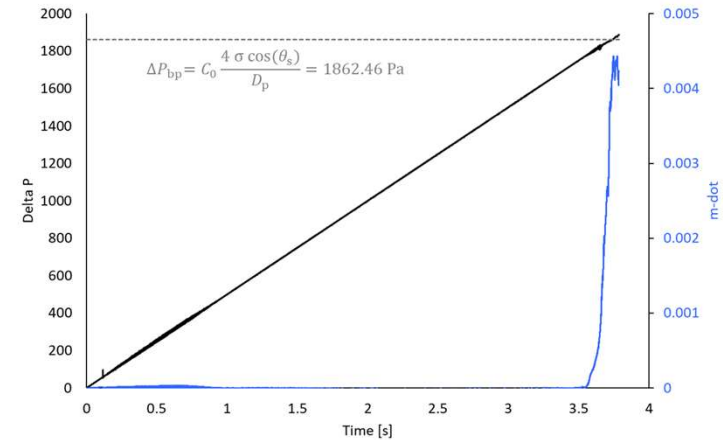
Pressure Drop vs Flow Velocity



Summary so far

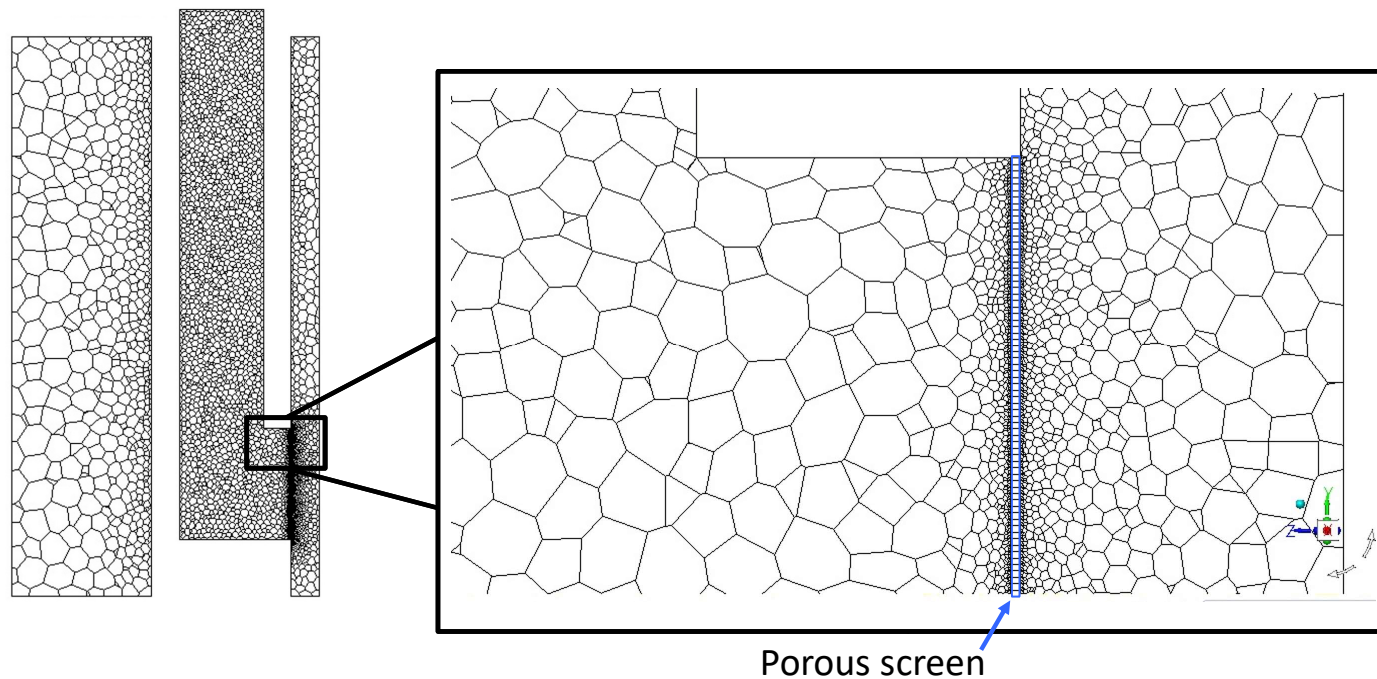
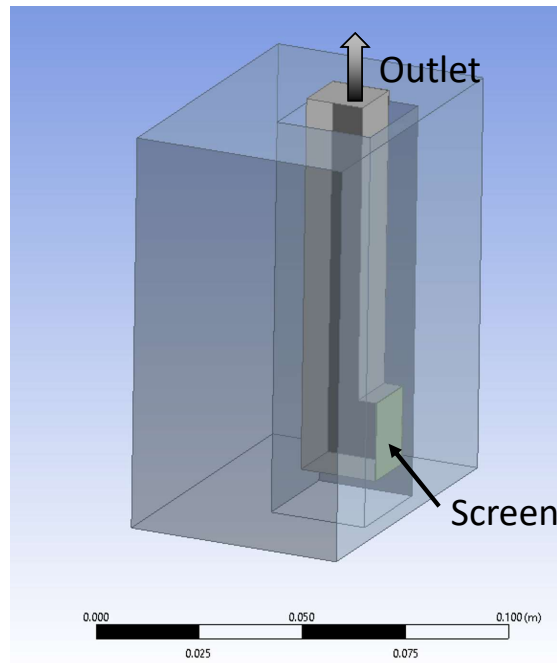


- ✓ Captured static physics
- ✓ Captured dynamic physics
- Full Tank Modeling (Ongoing Work)



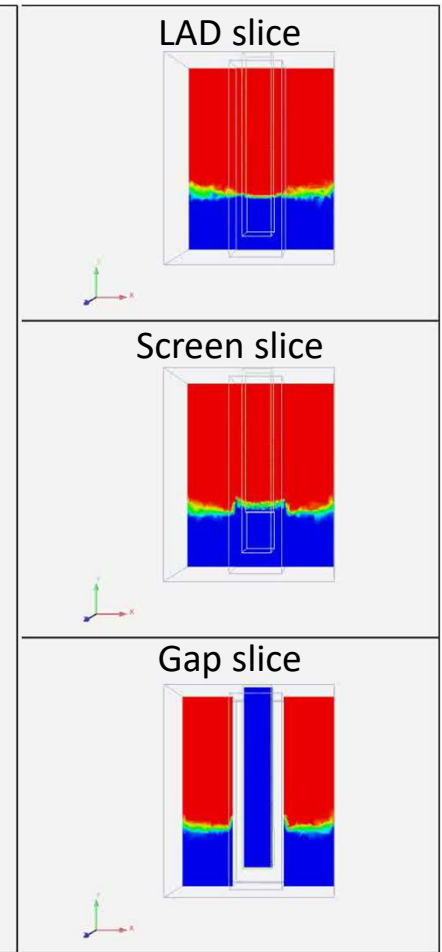
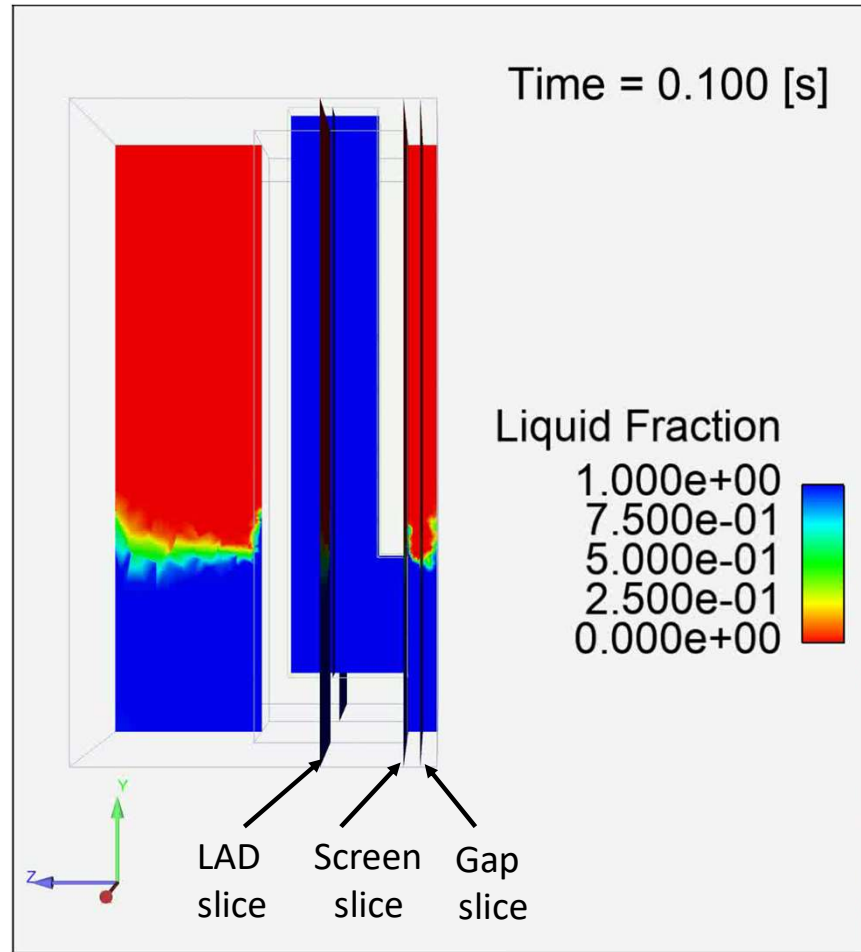
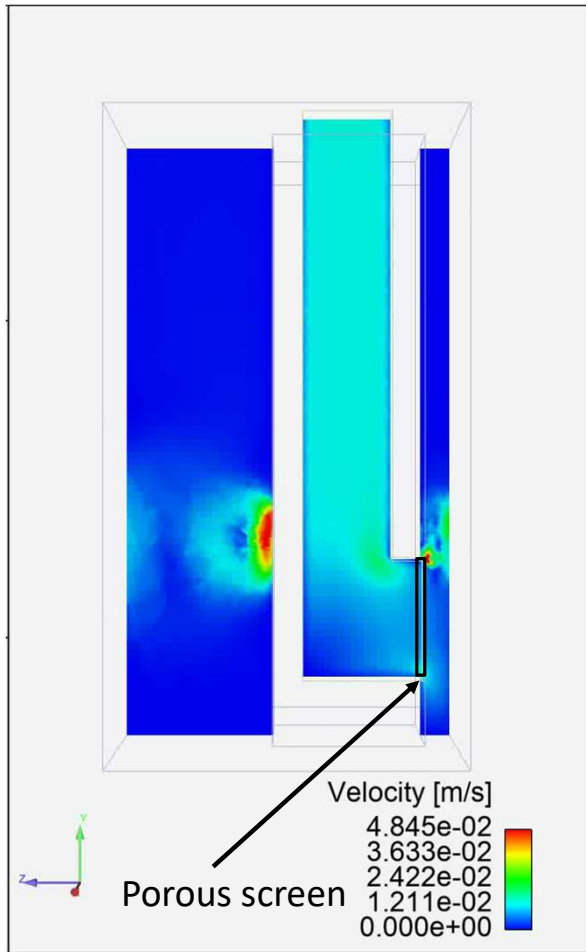
Full Tank Modeling – Coarse Mesh

- Coarse preliminary mesh has 943,790 cells
- Static barrier not implemented
- Looking at fluid reorientation





Full Tank Modeling – Coarse Mesh Animation



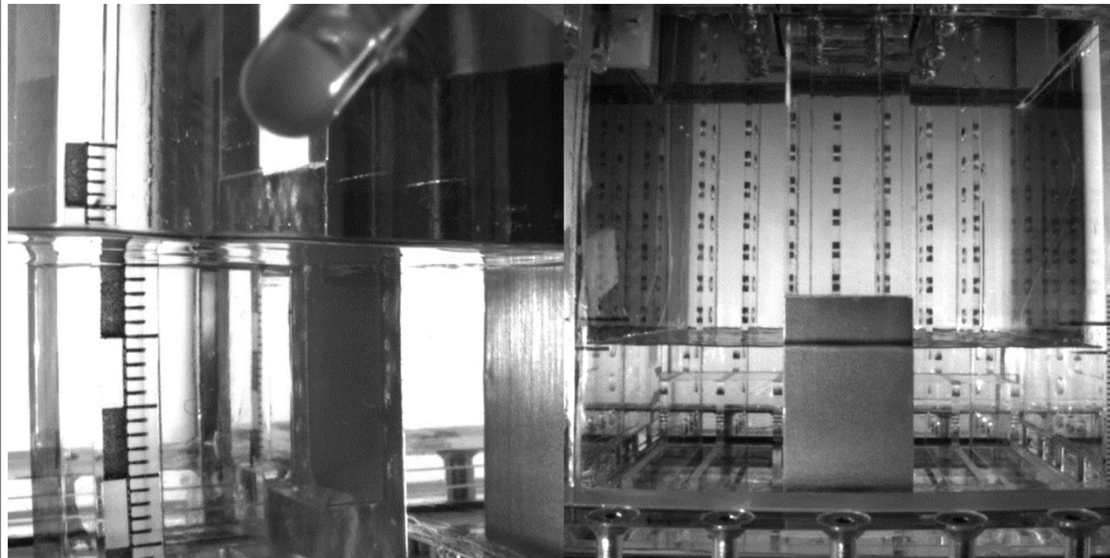
Full Tank Modeling – Coarse Mesh Animation vs. Experiment



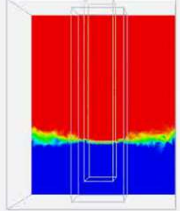
Time = 0.100 [s]

Liquid Fraction

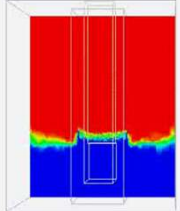
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7.500e-01
5.000e-01
2.500e-01
0.000e+00



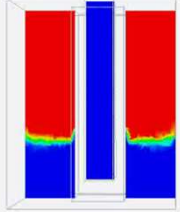
LAD slice



Screen slice

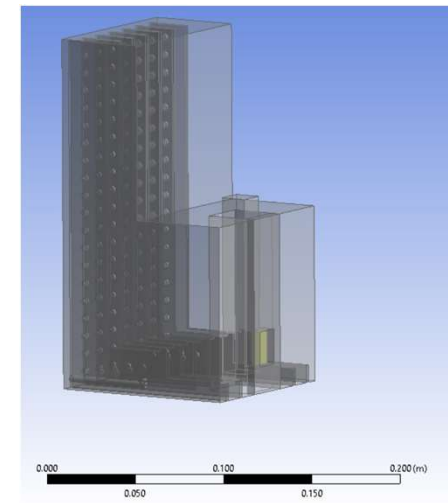
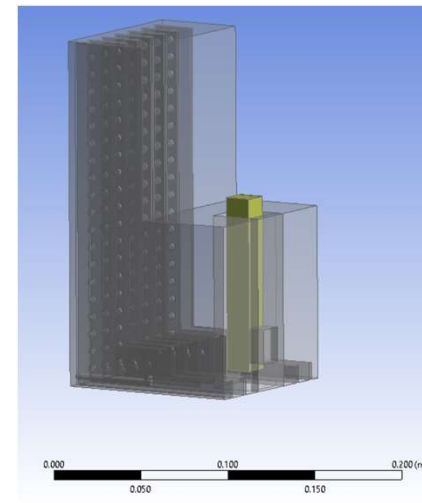
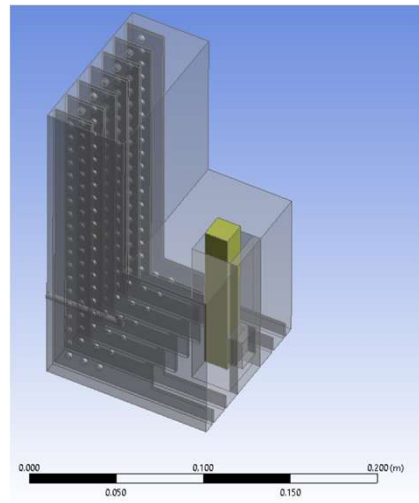
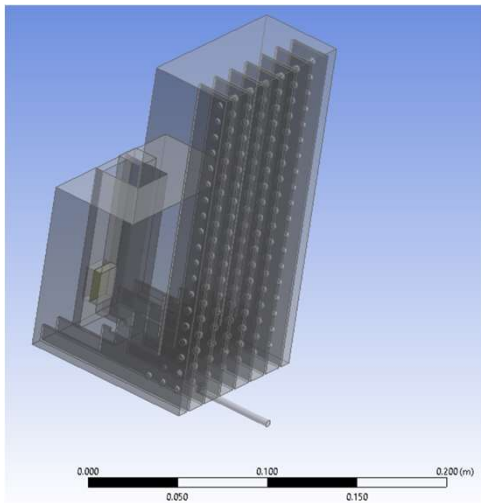


Gap slice



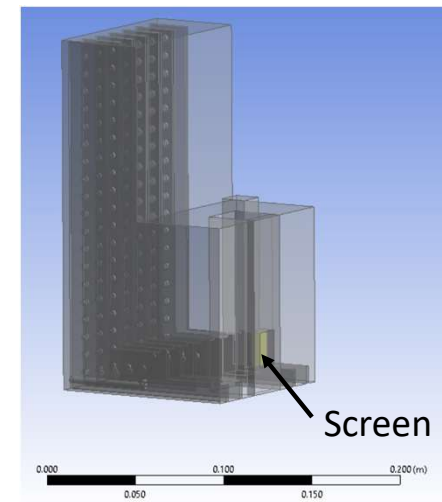
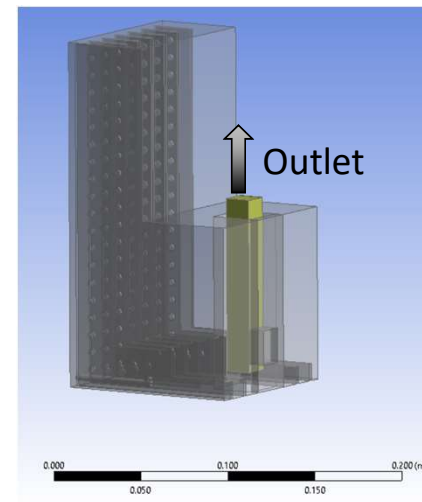
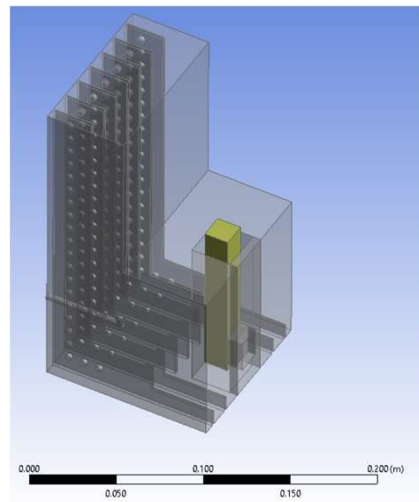
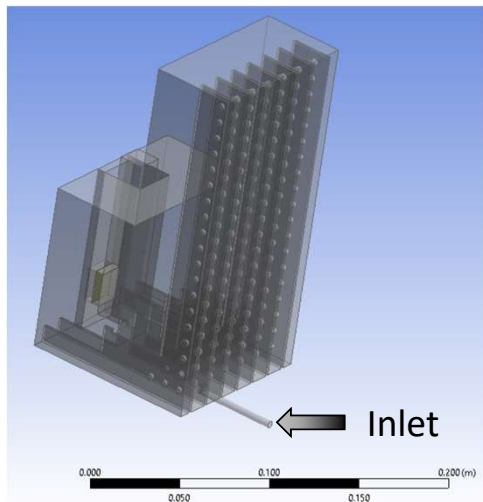
Full Tank Modeling – Setup and Geometry

- Geometry based on experiments performed and published by Shukla & Dreyer 2024
- Volume of Fluid (VOF) scheme with explicit formulation
- Sharp interface modeling
- Laminar fluid flow
- 5E-5 to 1E-5 sec time step size
- Pressure inlet and outlet
- Screen defined as porous zone
- Zero-gravity
- No slip walls

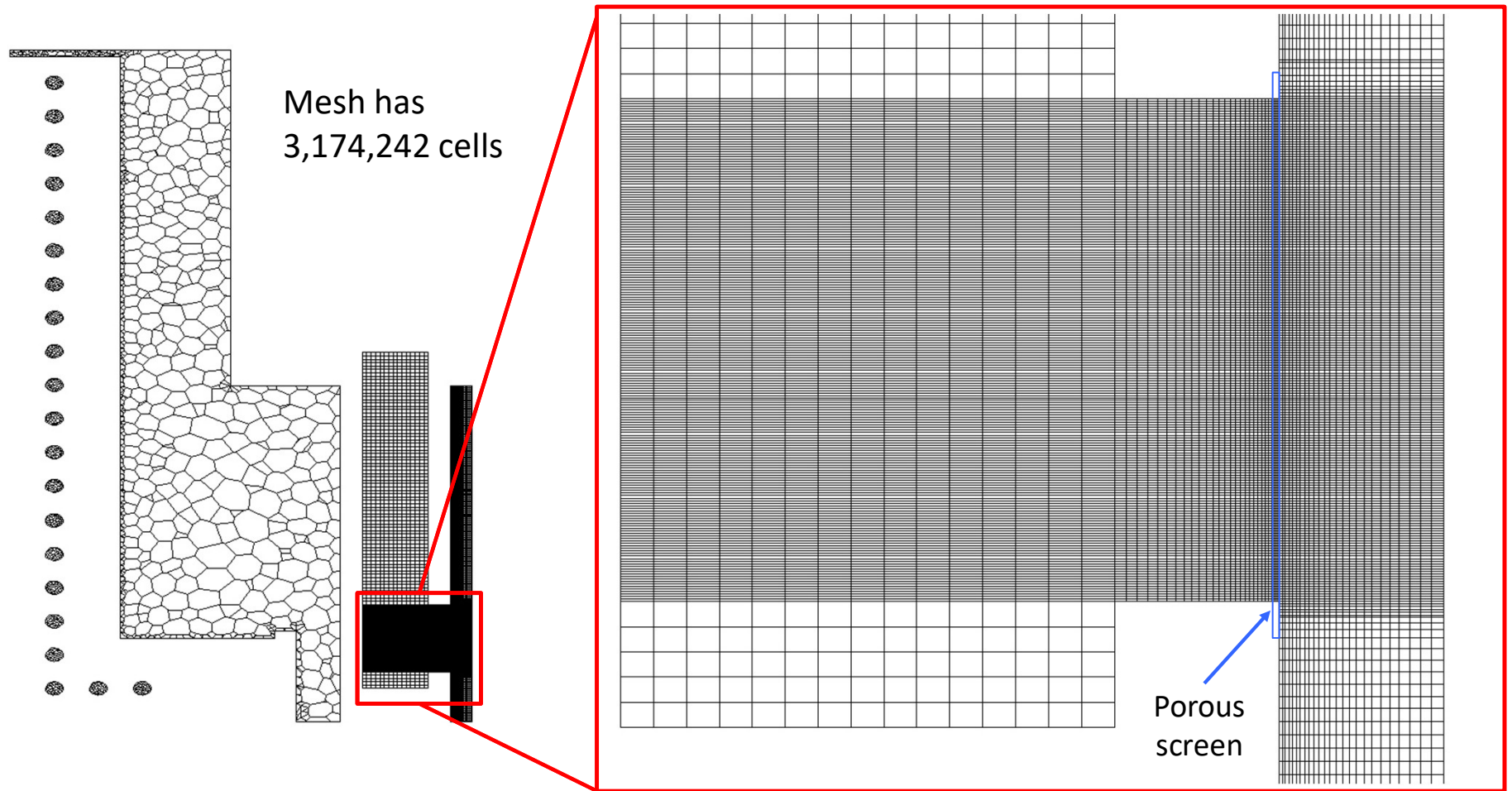
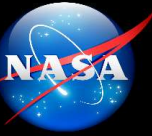


Full Tank Modeling – Setup and Geometry

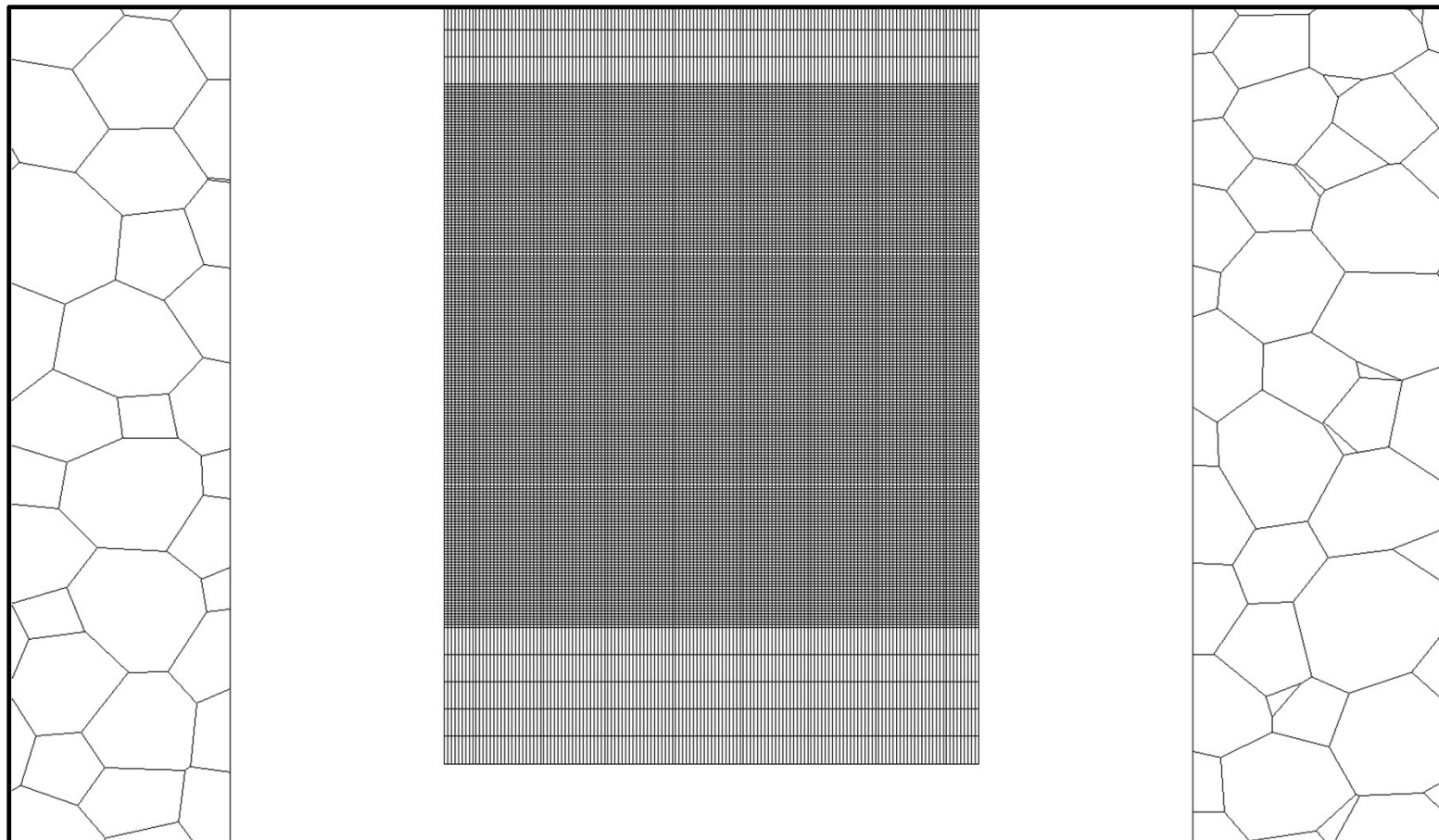
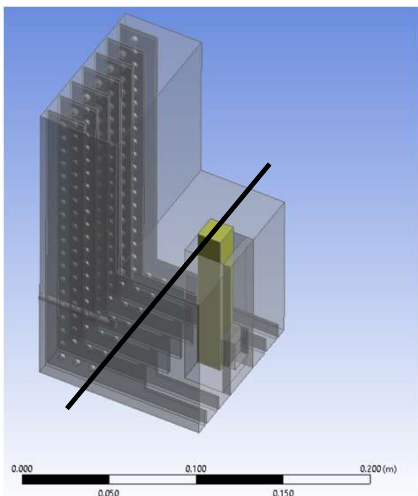
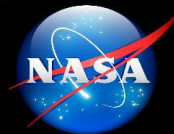
- Geometry based on experiments performed and published by Shukla & Dreyer 2024
- Volume of Fluid (VOF) scheme with explicit formulation
- Sharp interface modeling
- Laminar fluid flow
- 5E-5 to 1E-5 sec time step size
- Pressure inlet and outlet
- Screen defined as porous zone
- Zero-gravity
- No slip walls



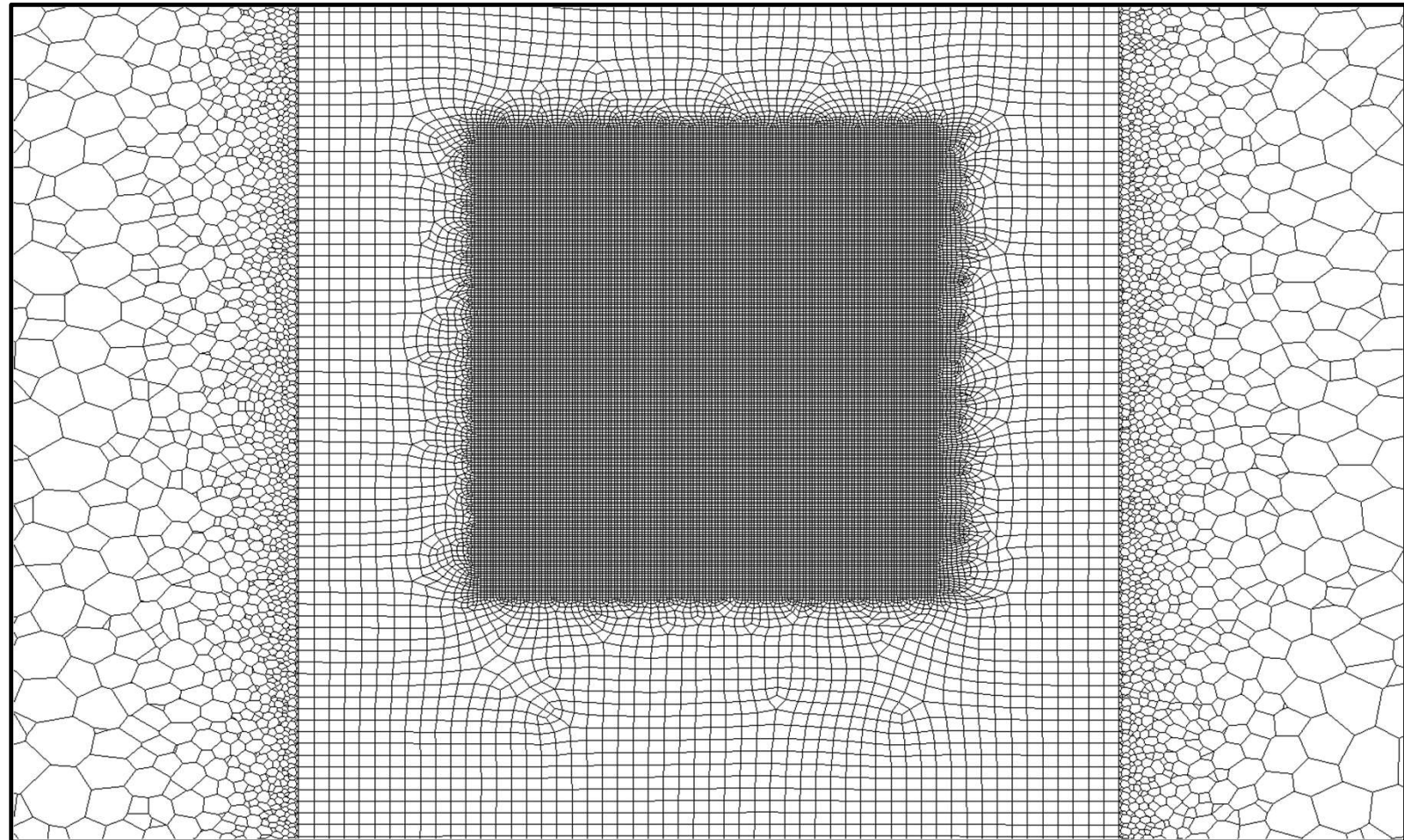
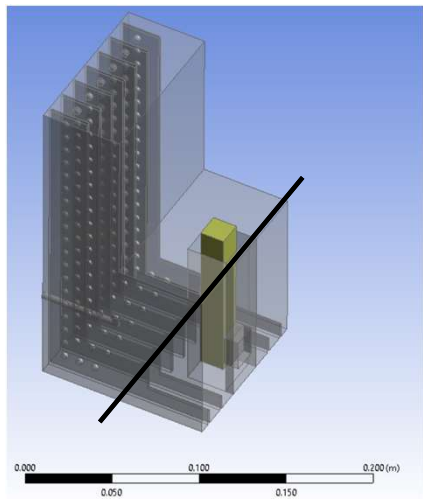
Full Tank Modeling – Mesh



Full Tank Modeling – Mesh

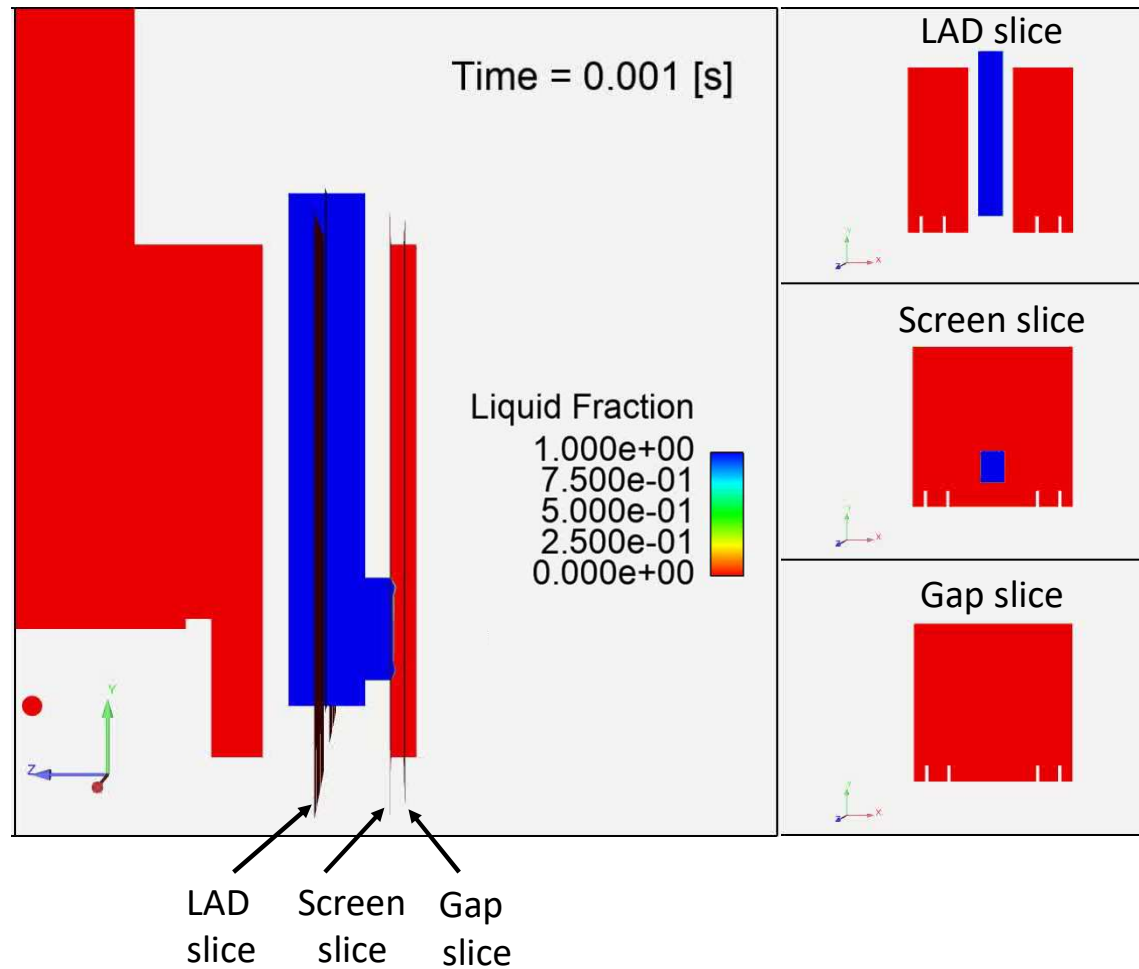
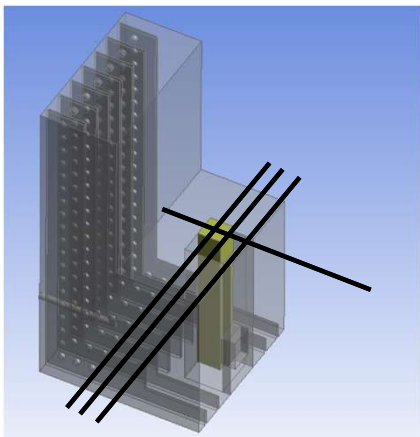


Full Tank Modeling – Mesh





Preliminary Results for Full Tank Modeling – Animation



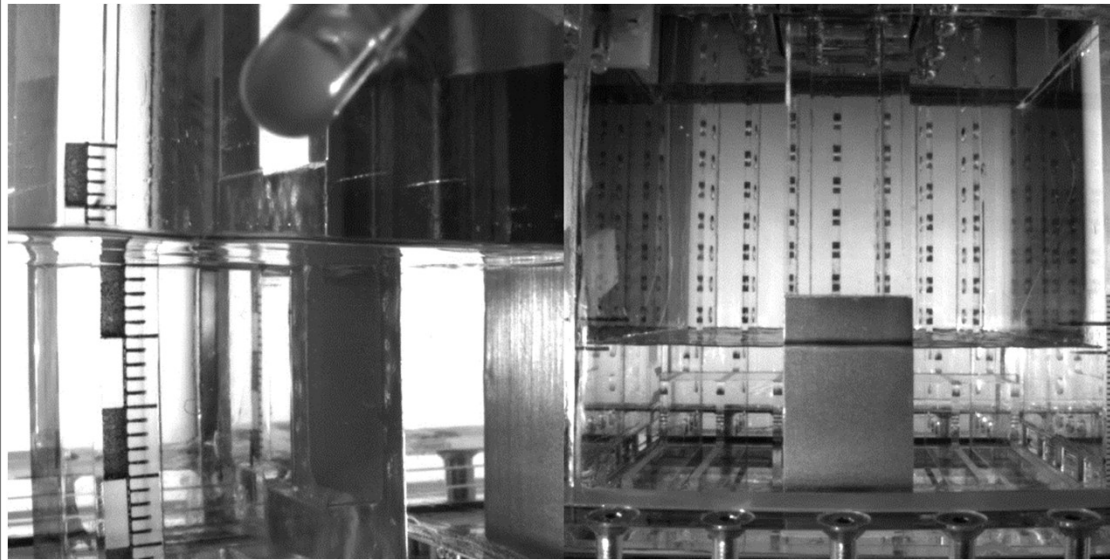
Full Tank Modeling – Coarse Mesh Animation vs. Experiment



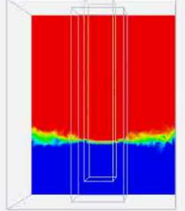
Time = 0.100 [s]

Liquid Fraction

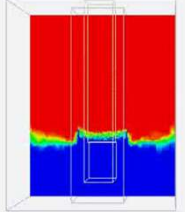
1.000e+00
7.500e-01
5.000e-01
2.500e-01
0.000e+00



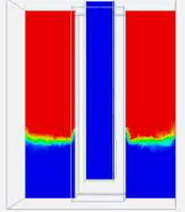
LAD slice



Screen slice

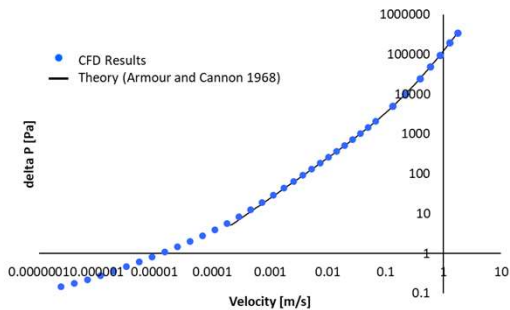


Gap slice





Acknowledgements



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