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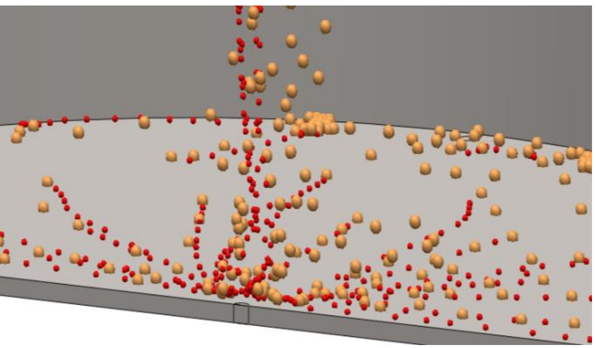
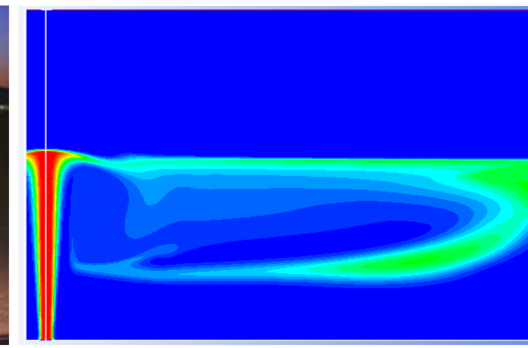
SAND2014-18266PE

Particle Resuspension in Water Distribution Storage Tanks





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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

- Objectives and Background
- Modeling
- Testing
- Conclusions

Objectives

- Perform simulations to understand where and when particles move during filling and draining cycles in a water distribution storage tank
- Determine impact of particle size, inlet diameter, flow rate, inlet location, and pipe extension on potential for particle resuspension
- Perform tests to verify models and characterize particle resuspension during filling and draining of a small-scale tank

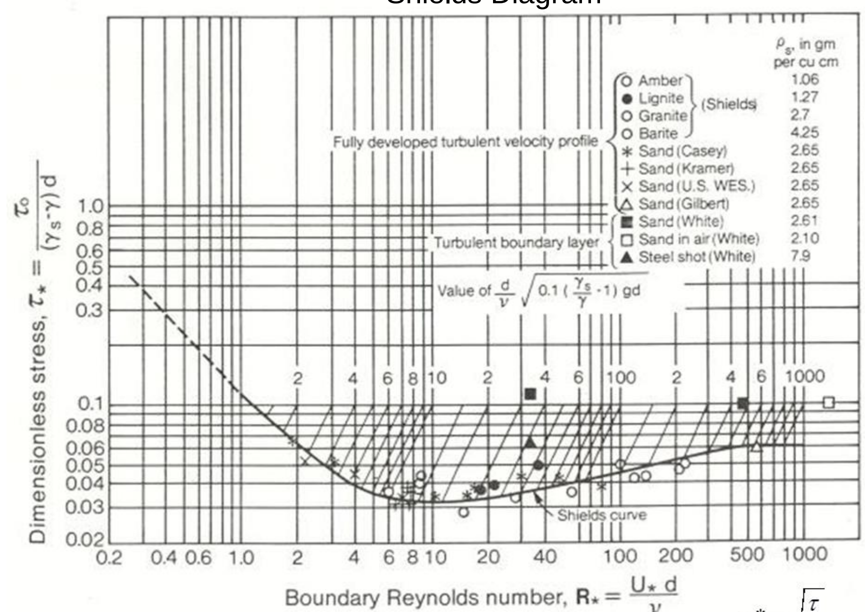
Overview

- Objectives and Background
- Modeling
- Testing
- Conclusions

Particle Resuspension Models

- Shields Diagram (1936)
  - Shields diagram yields larger required critical shear stresses to resuspend smaller particles (low boundary Reynolds numbers < ~2)
- Beheshti Movability Number (2008)
  - This model yields the lowest critical shear stress required to resuspend small particles (low boundary Reynolds numbers < ~2)
  - This model was shown to match available data the best

Shields Diagram



$$u^* = \sqrt{\frac{\tau}{\rho}}$$

$$\frac{u_{*c}}{w_s} = \begin{cases} 9.6674 \times D_*^{-1.57}, & D_* \le 10 \\ 0.4738 \times D_*^{-0.226}, & D_* > 10 \end{cases}$$

Beheshti Movability Number

$$w_s = \frac{A\nu}{Bd'}\left[\sqrt{\frac{1}{4} + \left(\frac{4B}{3A^2}D_*'^{\,3}\right)^{1/a}} - \frac{1}{2}\right]^a$$

$$A = 53.5e^{-0.65S_f}; \quad B = 5.65e^{-2.5S_f}; \quad a = 0.7 + 0.9S_f$$

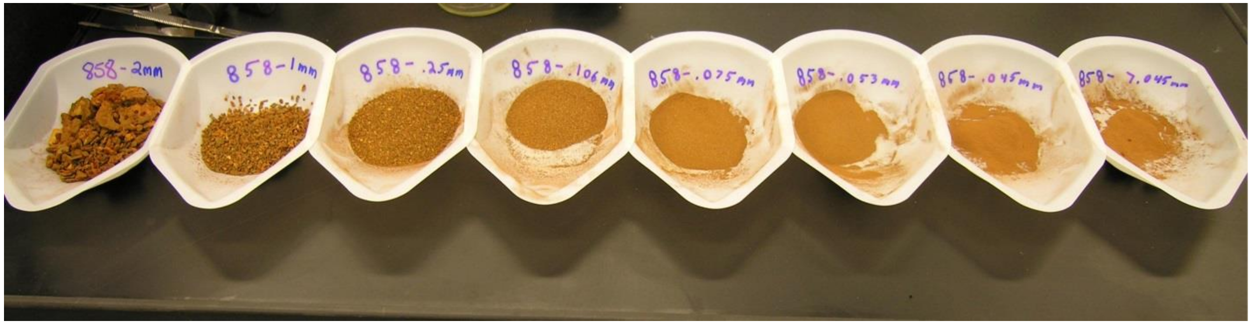
$$D_* = \left[(\rho_s - \rho)/\rho(g/\nu^2)\right]^{1/3} d$$

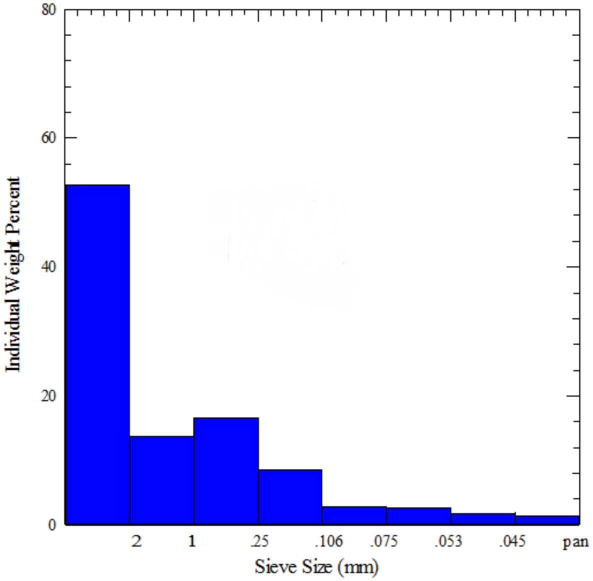
S_f = 0.7 (Corey shape factor for naturally shaped sediments)

$$u_{*c} = \sqrt{\frac{\tau_c}{\rho}}$$

Sediment Particle Survey

Colorado Tower, Columbus, OH





Bin Number	1	2	3	4	5	6	7	8
Particle Diameter (mm)	>2	1-2	.25-1	.106-.25	.075-.106	.053-.075	.045-.053	<.045
Mass Fraction	.5279	.1372	.1657	.856	.277	.255	.171	.132
Number Fraction	3.83e-5	3.99e-5	3.36e-4	.0122	.0579	.1504	.2686	.5106

Two Simulation Studies

- Operational Study
  - Understand how particles move during filling and draining
- Parametric Study
  - Understand impact of features and parameters on particle resuspension

Operational Study

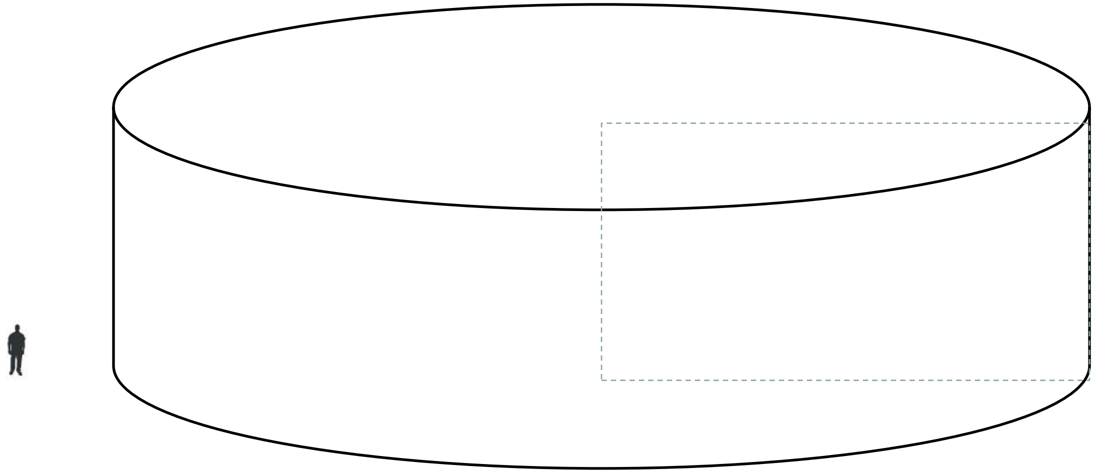
Albuquerque Water Authority Operating Procedure (German Andrade, personal communication)

- Tank filling/draining based on diurnal cycle
  - Higher demand ~8 AM – 8 PM (draining)
  - Lower demand ~8 PM – 8 AM (filling)
    - Reservoirs typically filled at night when electricity is cheaper
- Typical minimum water levels are 30-50% of tank capacity before pump stations turn on to fill them
  - Need to maintain water for fire emergencies
- Maximum operating water level is 95% of tank capacity
- Water in reservoirs is always dynamic (never stagnates)
  - At 95% capacity (full status) pumps/wells turned off

Model Development for Operational Study

- 2D axisymmetric domain (center nozzle)
- Two-phase volume-of-fluid model
- k-ω-sst turbulence model
- 8239 elements
- Courant number ≈ 1

Q = 0.631 m^3/s (10,000 GPM)



32’ height (initial water height = 16’)

24” nozzle diameter

126’ diameter

Model Procedure for Operational Study

- Modeling procedure
  - Distribute particles uniformly along bottom of tank
    - 2000 particles with 1 mm diameter
    - 2000 particles with 0.1 mm diameter
    - 2000 particles with 0.01 mm diameter
  - Simulate fill cycle until flow patterns stabilize
    - Use Shields or Beheshti criteria to determine if particles resuspend during fill cycle
  - *No settling time between filling and draining*
  - Simulate drain cycle until flow patterns stabilize
    - Use Shields or Beheshti criteria to determine if particles resuspend during drain cycle

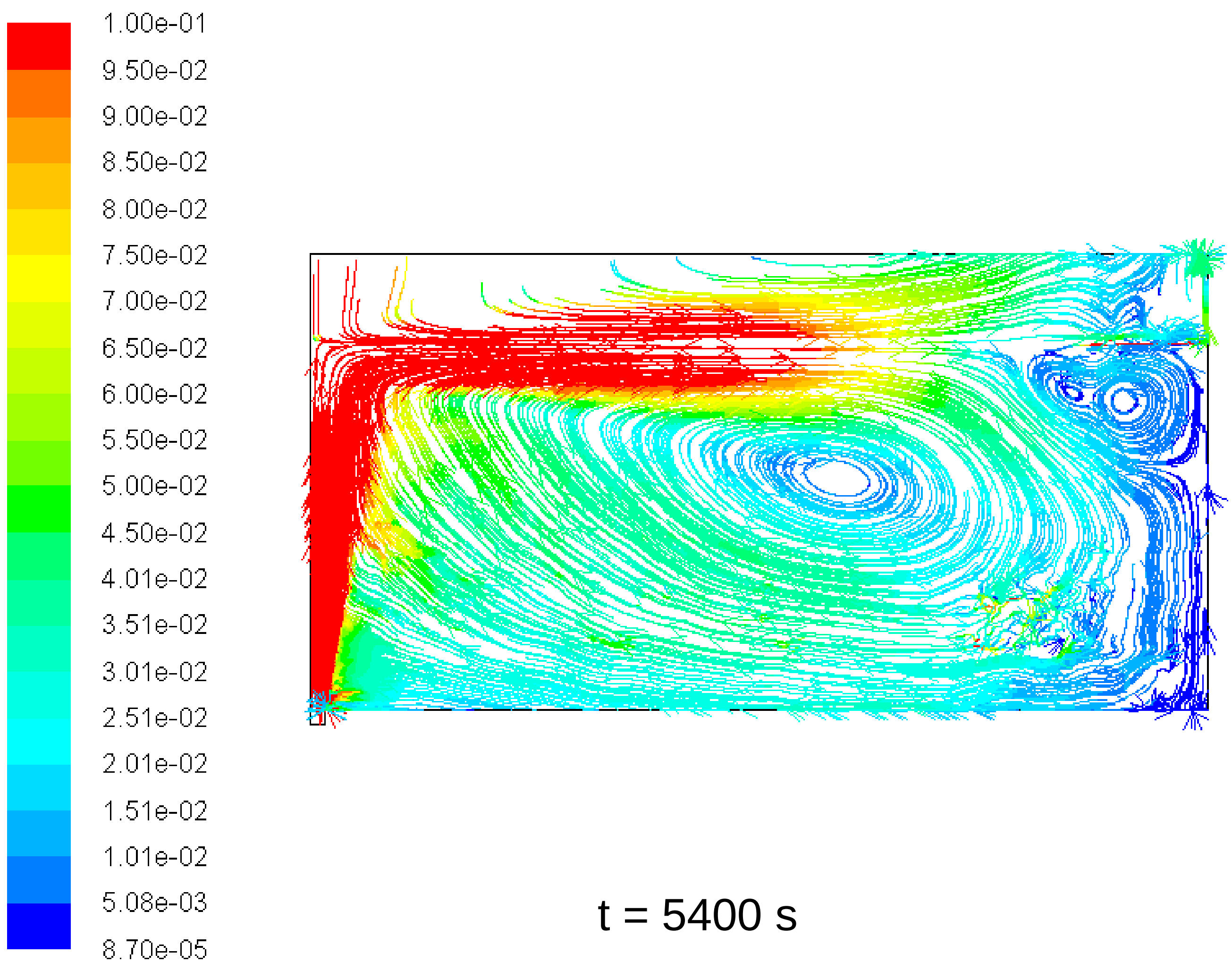
Operational Study Parameters

- Constant parameters
  - Diameter = 24 in
  - Center nozzle
  - Commercial scale
  - Three particle sizes (1, 0.1, 0.01 mm)
  - Start simulation with initial water level at 50% per German Andrade
- Two different flow rates; two different particle densities
  - High = 0.631 m^3/s, Low = 0.0315 m^3/s (German's specified low drain rate) **OR** 0.215 m^3/s (German's specified low fill rate)
  - 2650 kg/m^3, lower density (Lew is supposed to provide us with a lower density particle)
- Duration of simulations
  - High flow rate case (0.631 m^3/s)
    - Fill for 2 hours (so as not to exceed tank capacity)
    - Drain for 2 hours until water level goes back to 50% capacity
  - Low flow rate case (several options)
    - Low flow rate case (0.0315 m^3/s)
      - » Fill for 2 hours (for consistency with high flow rate case) **OR**
      - » Fill until 10% of tank volume is added (1.13e3 m^3)
        - » 1.13e3 m^3/0.0315 m^3/s = 3.49e4 s = 9.7 hours
      - » Drain for the same amount of time as the fill cycle
    - Low flow rate case (0.215 m^3/s)
      - » Fill until 10% of tank volume is added (1.13e3 m^3)
        - » 1.13e3 m^3/0.215 m^3/s = 5.26e3 s = 1.5 hours
      - » Drain for the same amount of time as the fill cycle
- Output
  - Animations of particle movement during duration of fill/drain cycles
  - Location and time that particles are resuspended
  - Location and time that particles are redeposited onto tank bottom after being resuspended
  - Number of particles exiting system during drain (and time of occurrence)

Modeling Notes

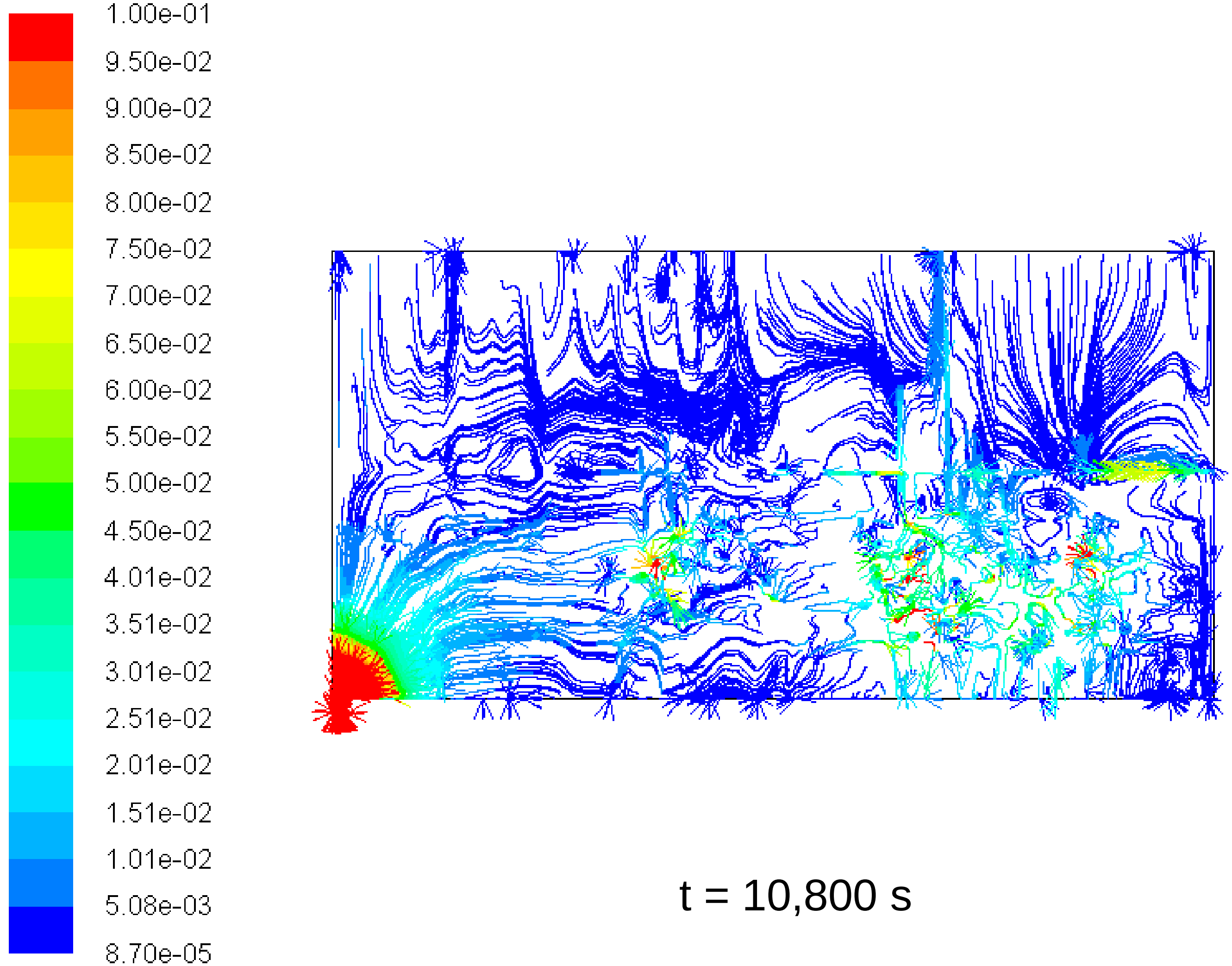
- Beheshti criteria chosen for final operational study (more accurate when compared to Shields criteria)
- Increase number of particles closer to nozzle to see more particle tracks of resuspended particles
- Implement surface tension model to prevent particles from passing above water surface

Flow pathlines during filling



t = 5400 s

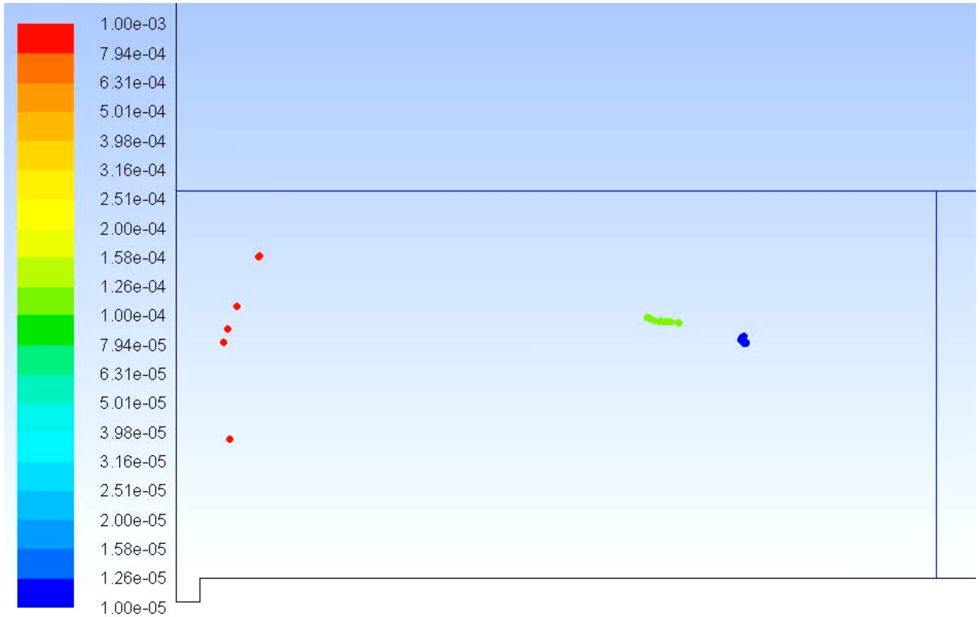
Flow pathlines during draining



t = 10,800 s

Particle Movement during Operational Study

- 24” center nozzle
- High flow rate (10,000 gpm)
- Shields criterion



Particle Traces Colored by Particle Diameter (mixture) (m) (Time=2.0200e+02) Aug 17, 2013
ANSYS Fluent 14.5 (axi, dp, pbns, vof, sstkw, transient)

Filling

Draining

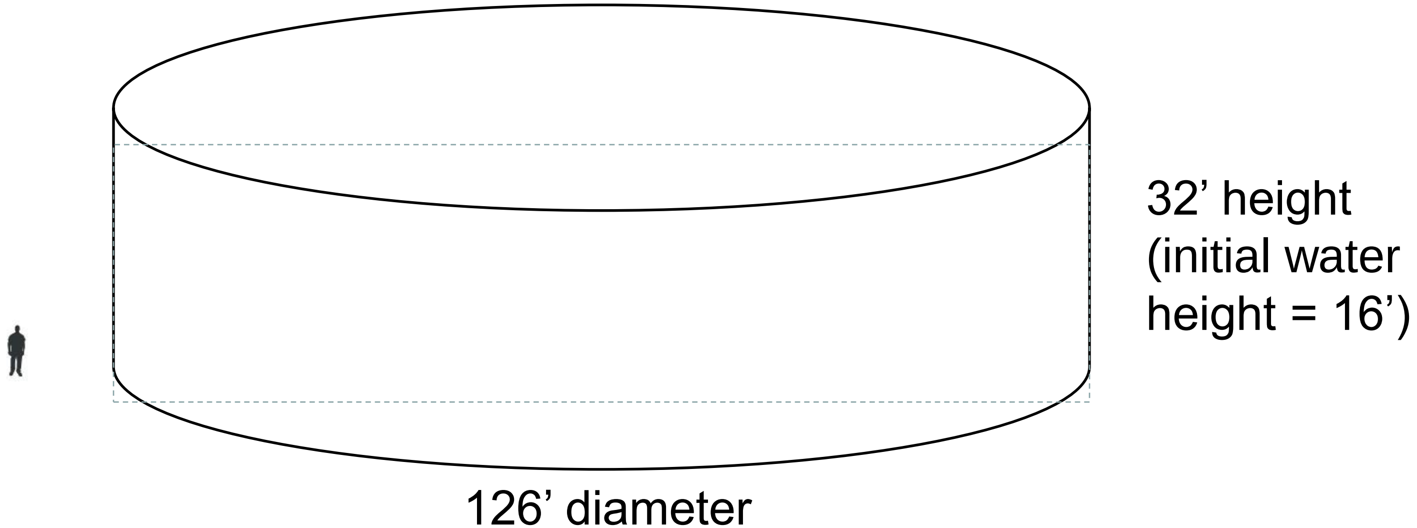
Summary of Operational Study

- Operational study was performed to evaluate particle movement during filling and draining cycles
  - Particle resuspension from tank bottom generally occurred immediately following start of either fillling or draining event
  - Entrainment of particles during filling typically carried particles further away from the inlet/outlet, making them less susceptible
  - Smaller particles (0.01 mm) were more susceptible to resuspension and entrainment
  - Recirculation zones of particles near the inlet/outlet were observed
  - Greater shear stress during draining led to more particle resuspension than during filling

Parametric Study

Model Development for Parametric Study

- 3D half-symmetry (center nozzle and near-wall nozzle)
- Two-phase volume-of-fluid model
- k-ω-sst turbulence model
- 670,000 elements (slight variations with different configurations and nozzle dimensions)
- Courant number ≈ 1



Design of Experiments for Parametric Study

(bounding values from ABQ Water Authority – German Andrade, personal communication)

Filling			
DoE Study	Flow Rate (m^3/s)	Nozzle Diameter (in)	Nozzle Placement
1	0.631	36	Near Side Wall
2	0.215	24	Center
3	0.631	24	Near Side Wall
4	0.631	36	Center
5	0.215	36	Center
6	0.215	24	Near Side Wall
7	0.215	36	Near Side Wall
8	0.631	24	Center

Drainage			
DoE Study	Flow Rate (m^3/s)	Nozzle Diameter (in)	Nozzle Placement
1	0.631	36	Center
2	0.631	36	Near Side Wall
3	0.0315	24	Near Side Wall
4	0.631	24	Center
5	0.0315	24	Center
6	0.0315	36	Near Side Wall
7	0.631	24	Near Side Wall
8	0.0315	36	Center

Model Procedure for Parametric Study

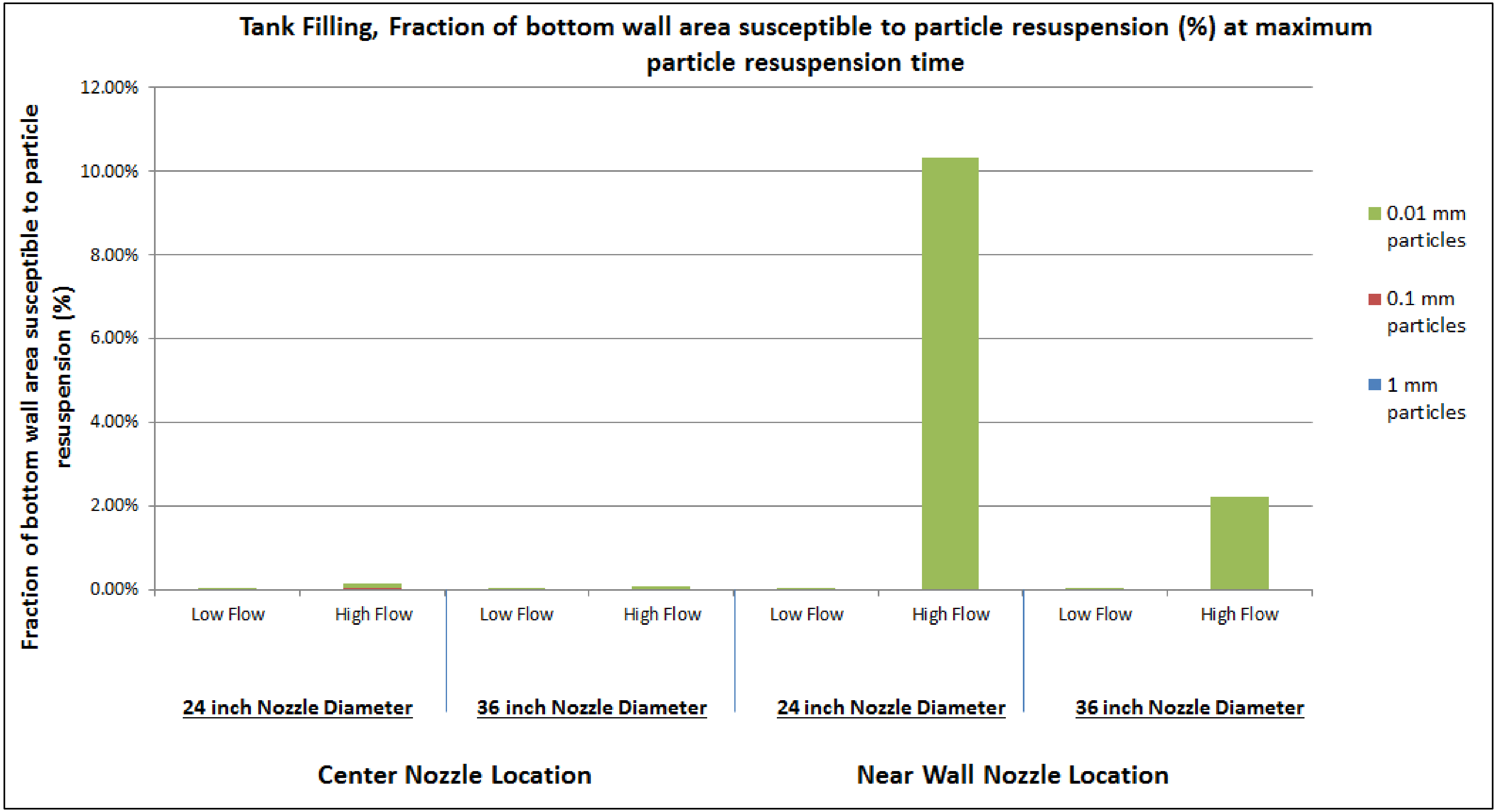
- Modeling procedure
  - Run simulations until the shear stresses are relatively steady
  - Shear stress at each element along bottom wall is recorded to determine if resuspension can occur based on different resuspension models
    - Fraction of cells with resuspension is used as a metric for different scenarios

Results of Parametric Study

Filling			**Percentage of Particles Resuspended**		
Nozzle Placement	**Nozzle Diameter (in)**	**Flow Rate (m^3/s)**	**1 mm**	**0.1 mm**	**0.01 mm**
Center	24	0.215	0.00	0.21	0.79
Center	24	0.631	0.21	0.57	2.03
Center	36	0.215	0.00	0.00	0.30
Center	36	0.631	0.01	0.17	1.30
Near Side Wall	24	0.215	0.00	0.00	0.52
Near Side Wall	24	0.631	0.01	0.28	9.24
Near Side Wall	36	0.215	0.00	0.00	0.25
Near Side Wall	36	0.631	0.01	0.43	9.65

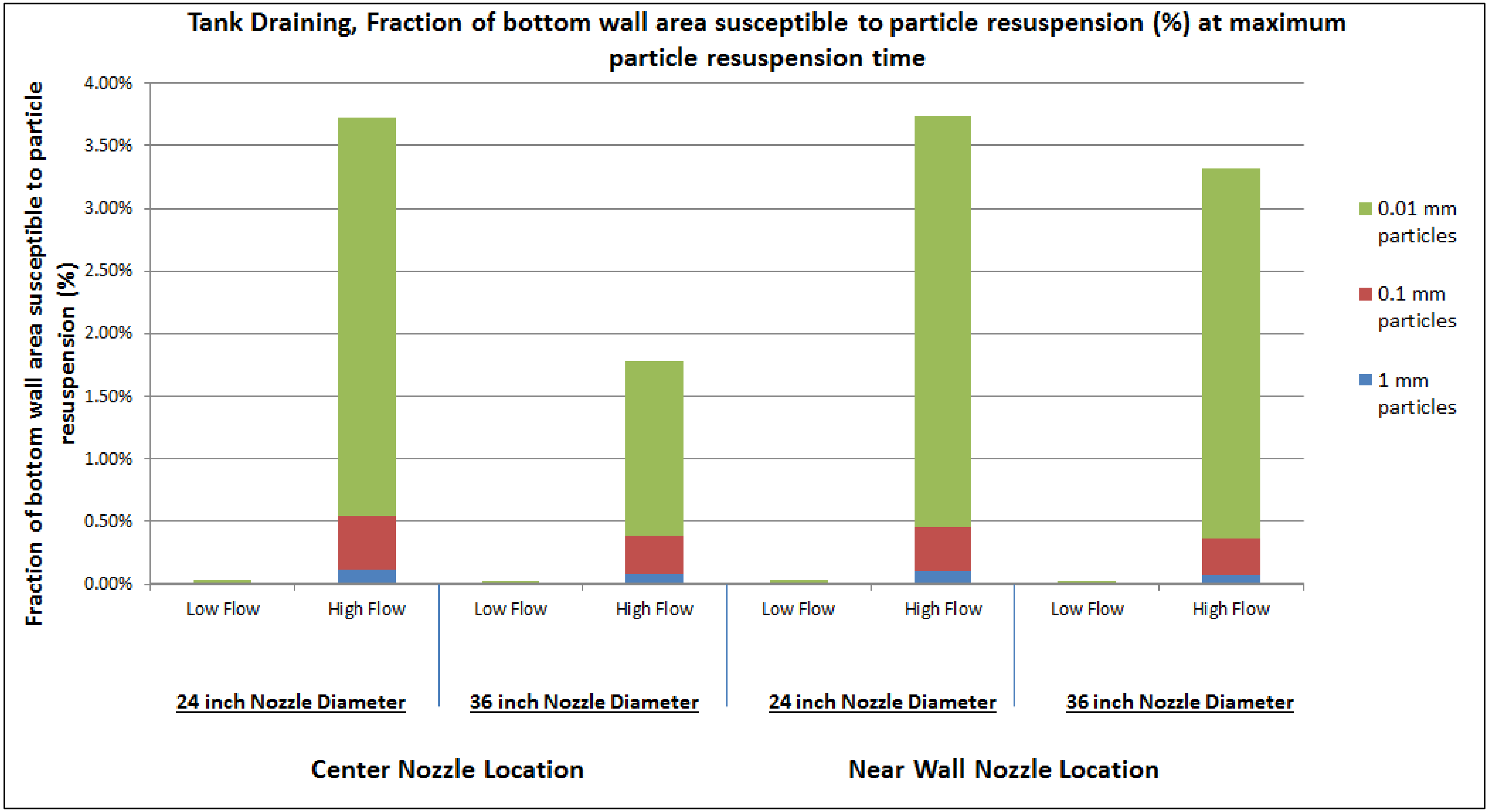
Draining			**Percentage of Particles Resuspended**		
Nozzle Placement	**Nozzle Diameter (in)**	**Flow Rate (m^3/s)**	**1 mm**	**0.1 mm**	**0.01 mm**
Center	24	0.0315	0.00	0.00	1.04
Center	24	0.631	2.21	3.72	10.76
Center	36	0.0315	0.00	0.00	0.89
Center	36	0.0315	1.98	3.98	7.02
Near Side Wall	24	0.0315	0.00	0.00	1.02
Near Side Wall	24	0.631	2.13	3.75	11.03
Near Side Wall	36	0.0315	0.00	0.00	0.41
Near Side Wall	36	0.631	1.81	3.95	11.30

Results for Filling



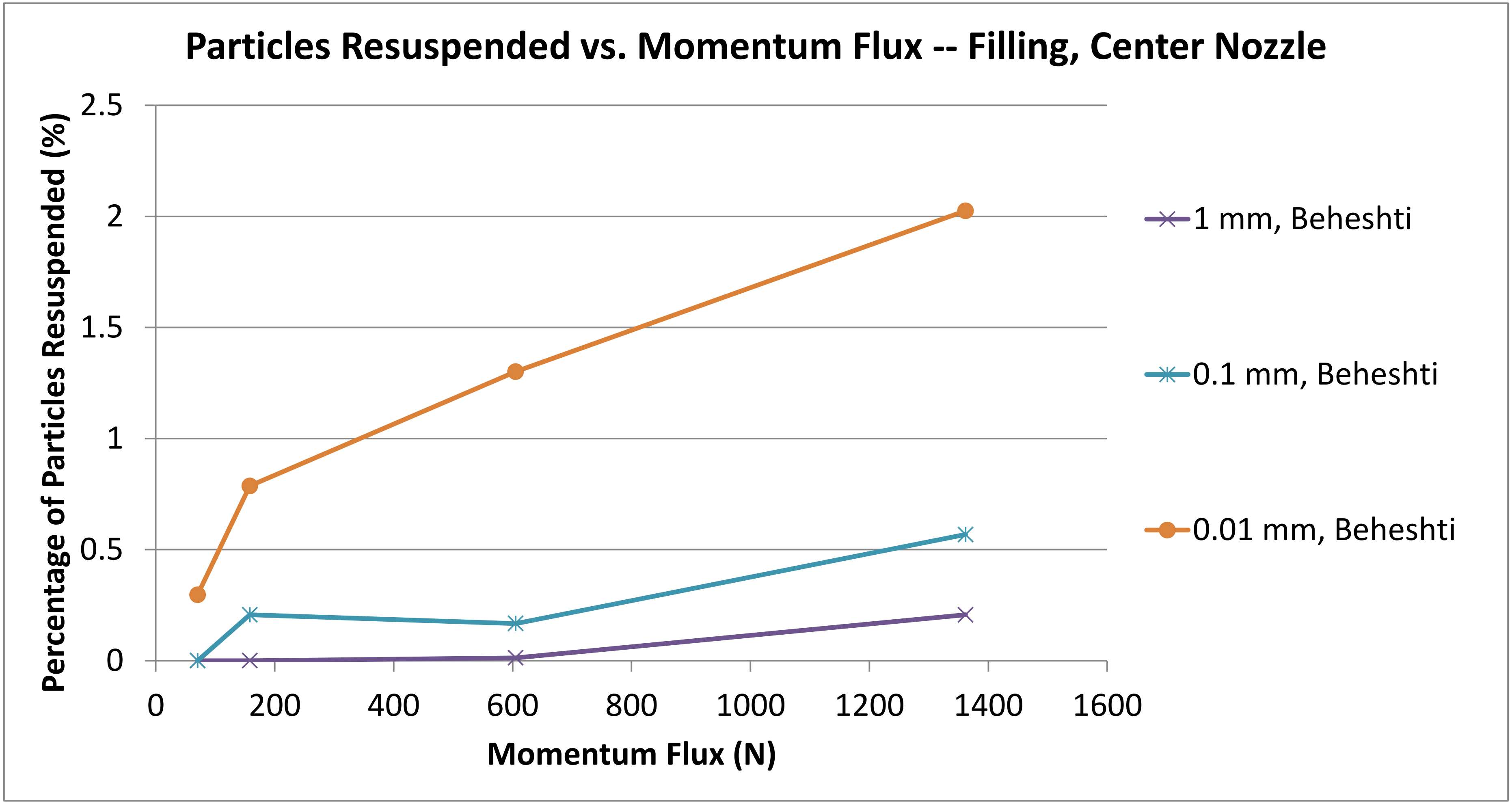
- Low flow = 0.215 m^3/s
- High flow = 0.631 m^3/s

Results for Draining



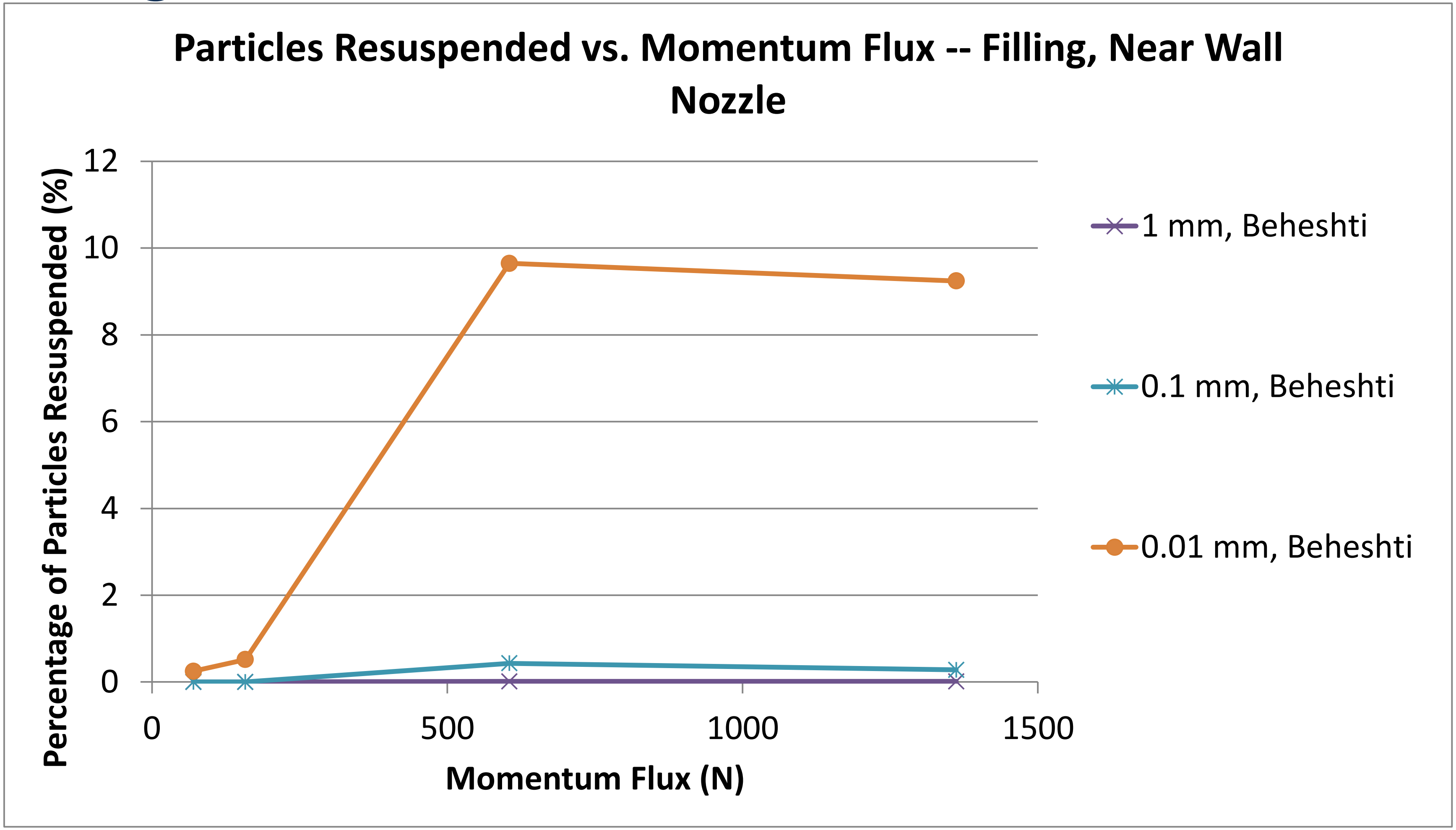
- Low flow = 0.215 m^3/s
- High flow = 0.631 m^3/s

Particles Resuspended vs. Momentum Flux – Filling, Center Nozzle



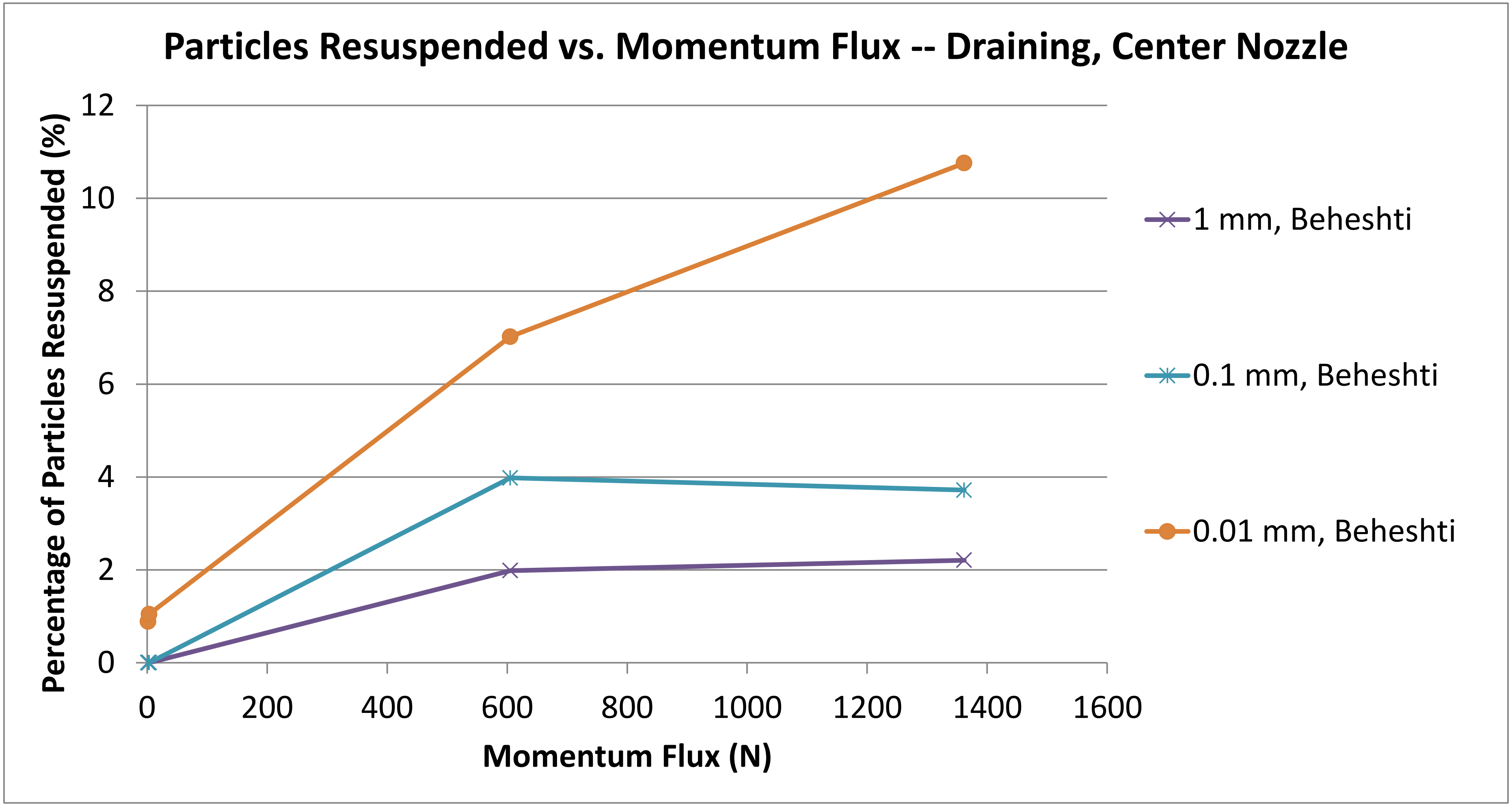
- Momentum flux = $(4/pi)*\rho*(Q/d)^2$

Particles Resuspended vs. Momentum Flux – Filling, Near Wall Nozzle



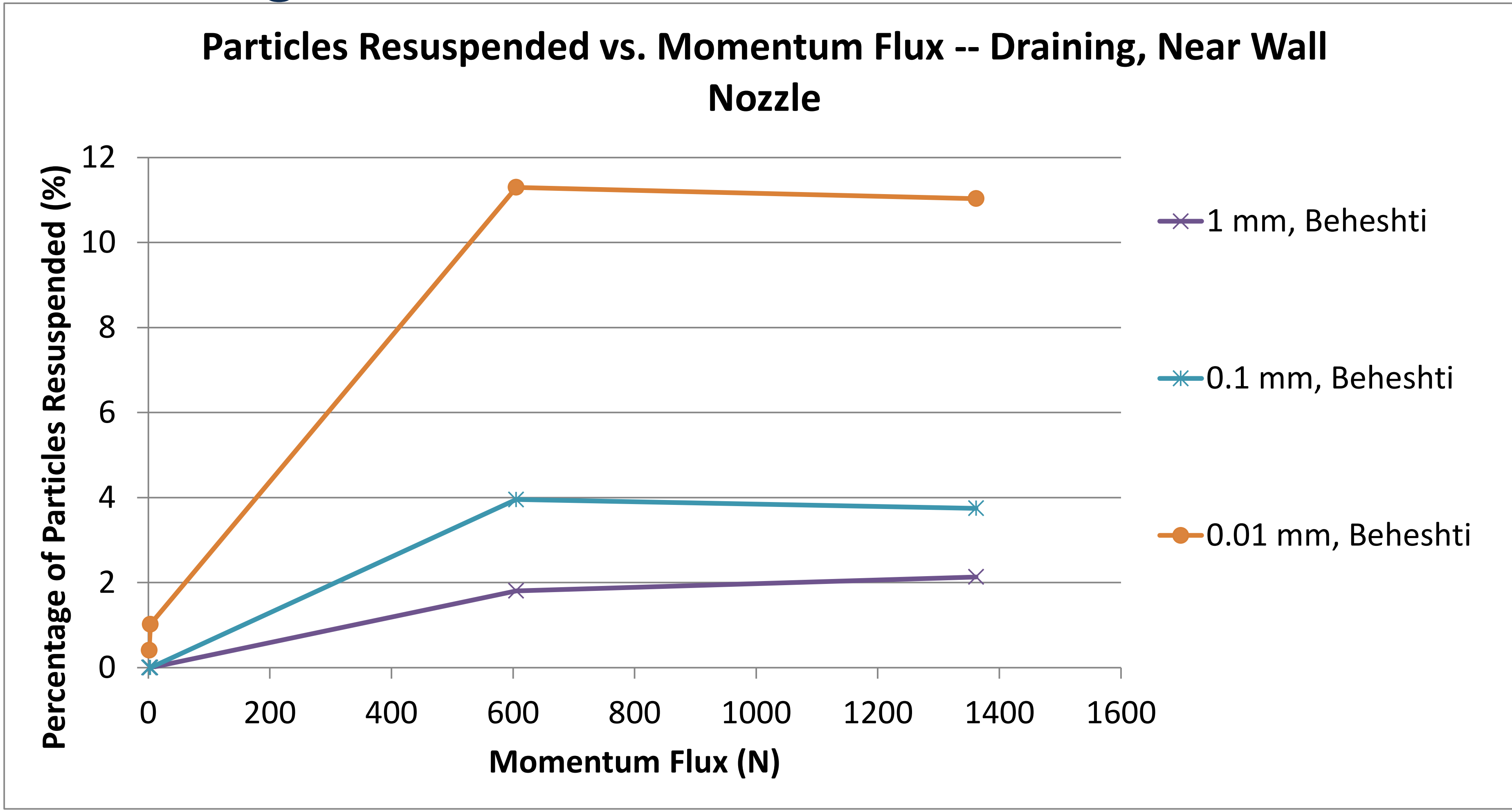
- Momentum flux = $(4/pi)*\rho*(Q/d)^2$

Particles Resuspended vs. Momentum Flux – Draining, Center Nozzle



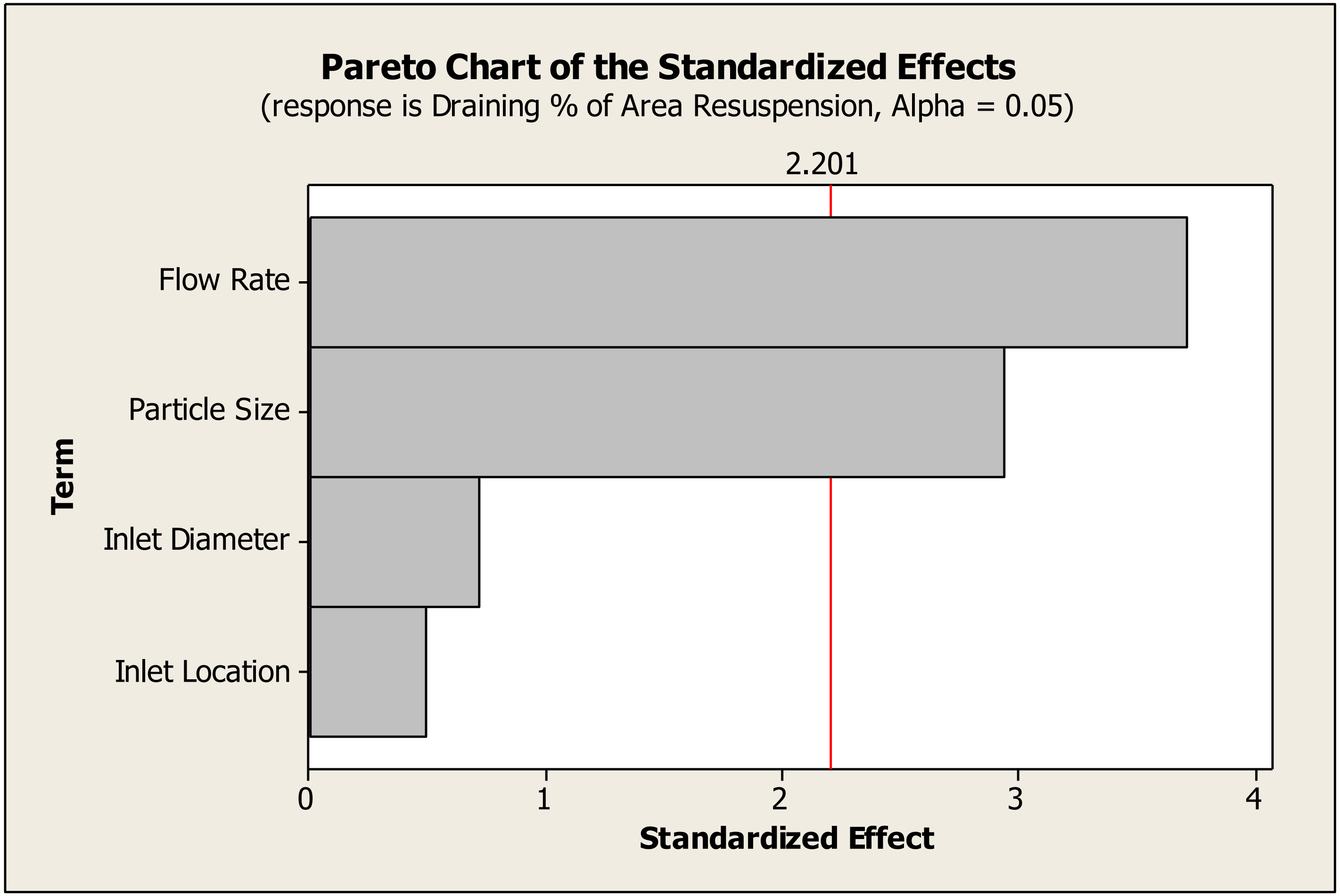
- Momentum flux = $(4/pi)*\rho*(Q/d)^2$

Particles Resuspended vs. Momentum Flux – Draining, Near Wall Nozzle



- Momentum flux = $(4/pi)*\rho*(Q/d)^2$

Importance of Factors on Number of Particles Resuspended



Summary of Parametric Study

- Filling
  - Particle size, particle flow rate, and inlet location were important factors
    - Smaller particles (0.01 mm) were more susceptible to resuspension
      - Near-wall inlet yielded more resuspension
      - Higher flow rates yielded more resuspension
- Draining
  - Flow rate and particle size were important factors
    - Smaller particles were more susceptible to resuspension, although the difference was less during draining than filling
    - In general, a larger percentage of particles was resuspended during draining vs. filling

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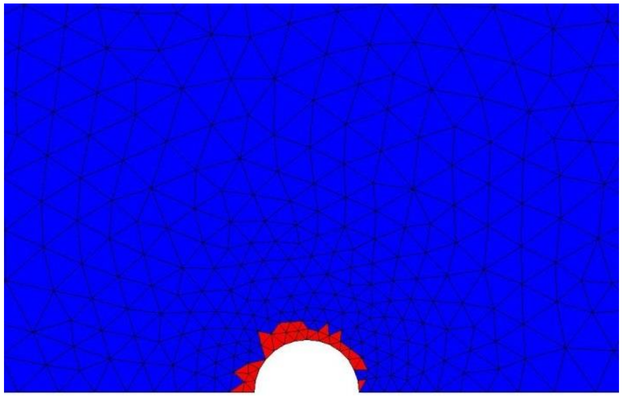
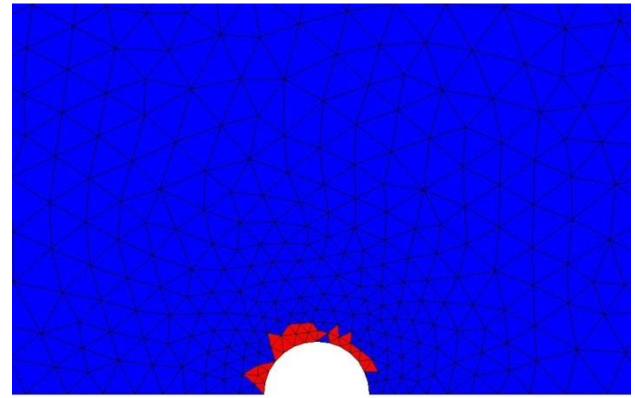
Where are the particles being resuspended?

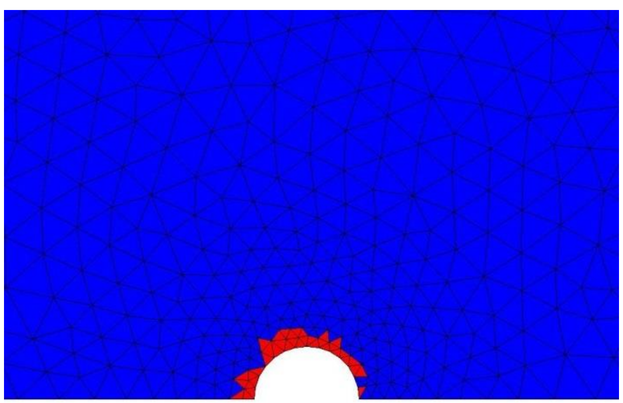
Locations (red) of Particle Resuspension during Filling for Case 8 (center nozzle) using Different Models



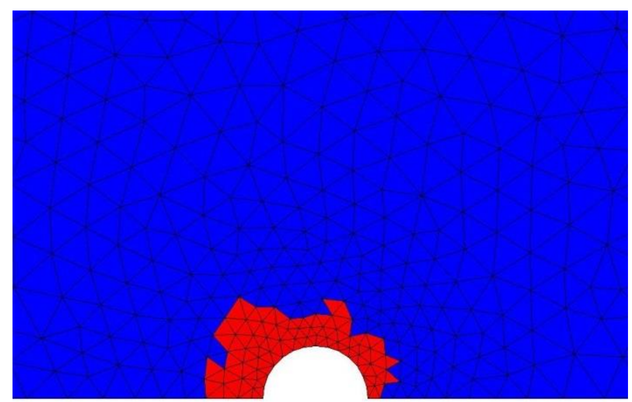
Shields (1936) 0.1 mm



Beheshti (2008) 0.1 mm

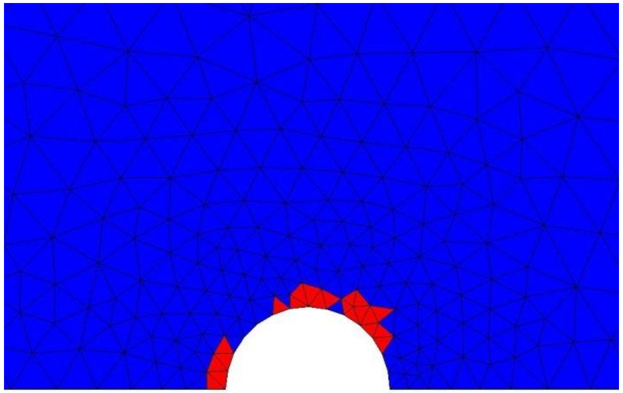


Shields (1936) 0.01 mm

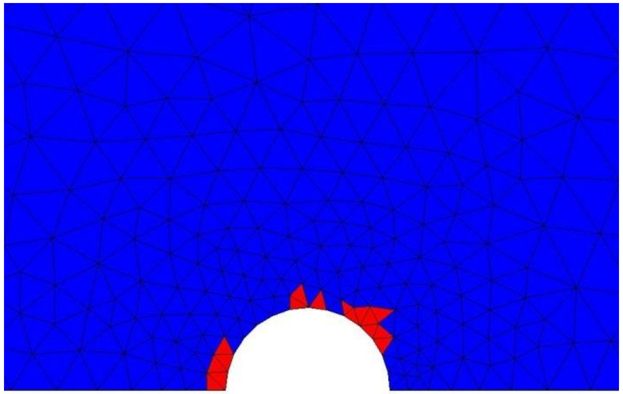


Beheshti (2008) 0.01 mm

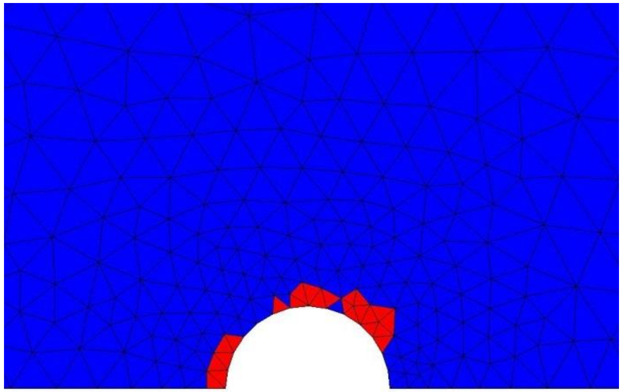
Locations (red) of Particle Resuspension during Filling for Case 3 (near-wall nozzle) using Different Models



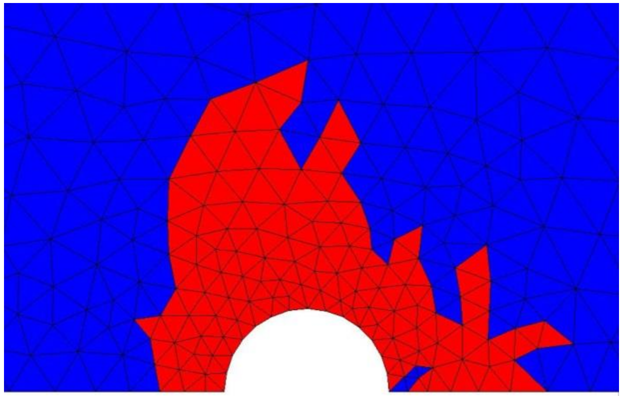
Shields (1936) 0.1 mm



Beheshti (2008) 0.1 mm

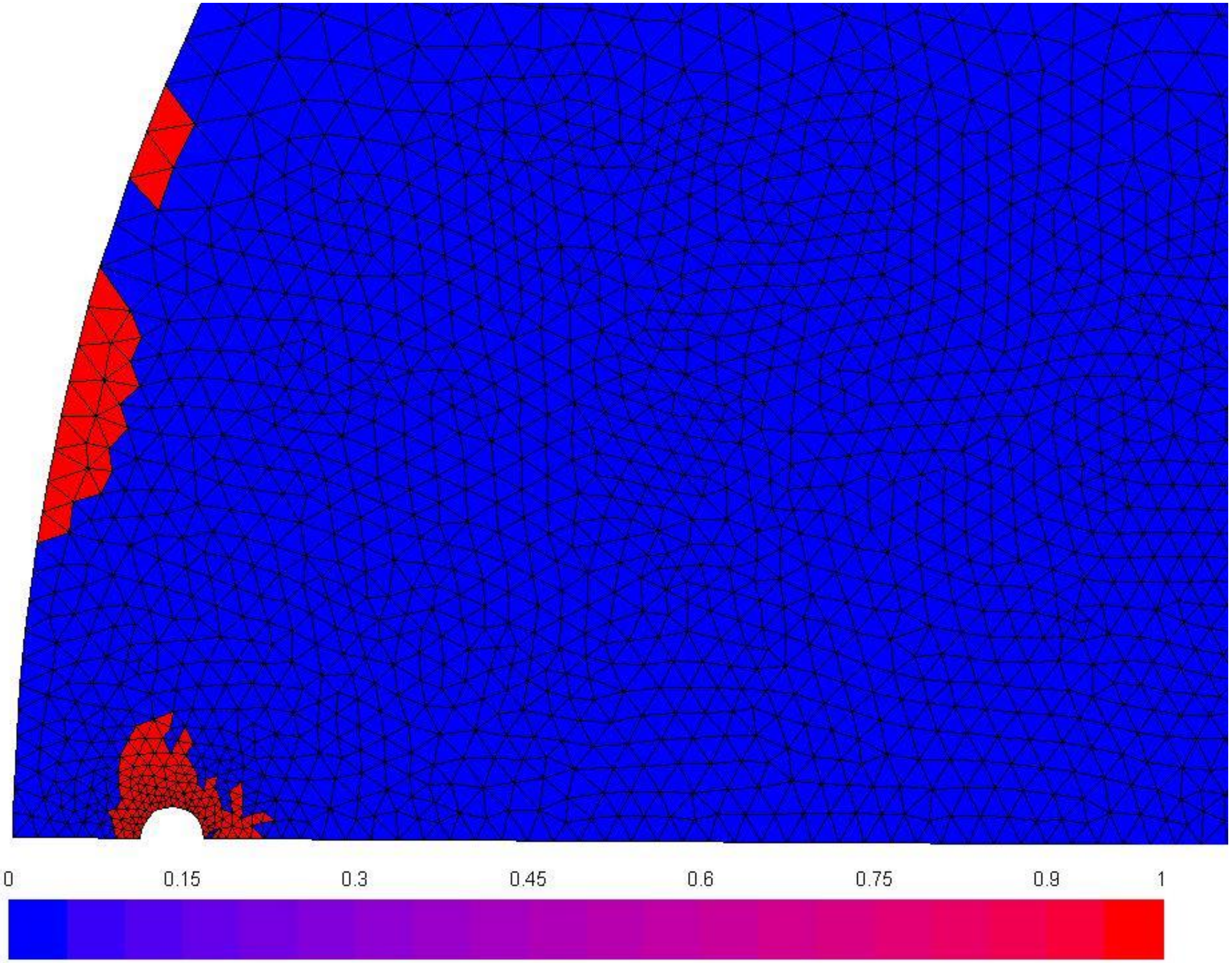


Shields (1936) 0.01 mm



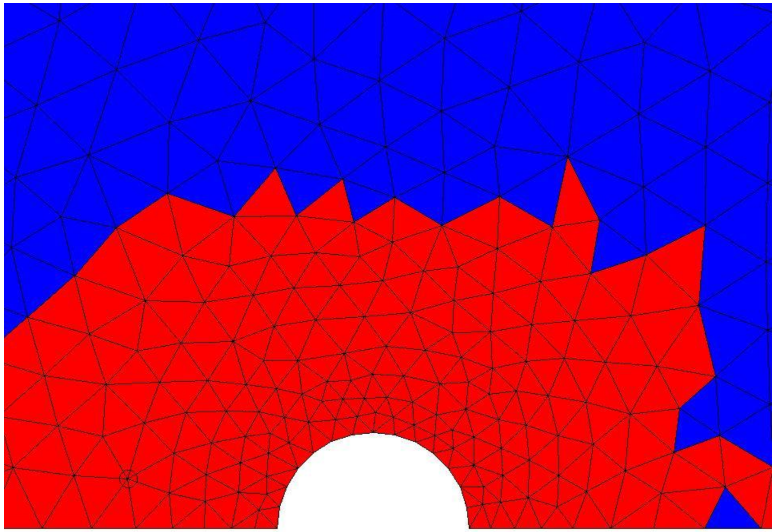
Beheshti (2008) 0.01 mm

Locations (red) of Particle Resuspension during Filling for Case 3 (Zoomed out)

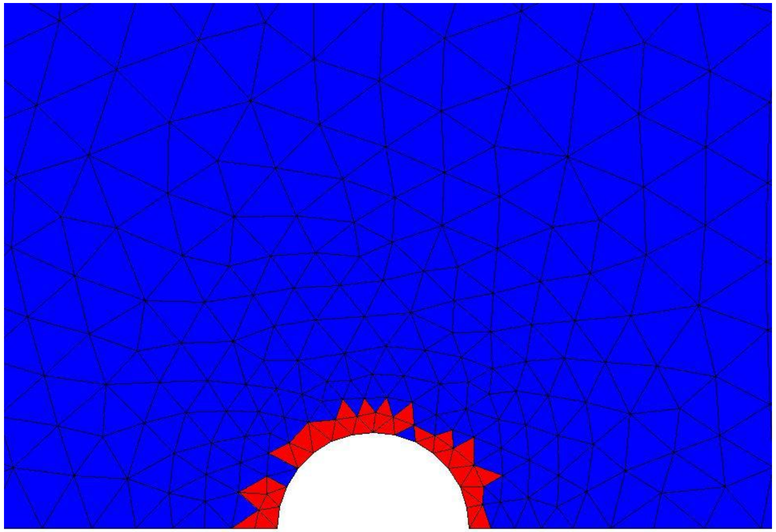


Beheshti (2008) 0.01 mm

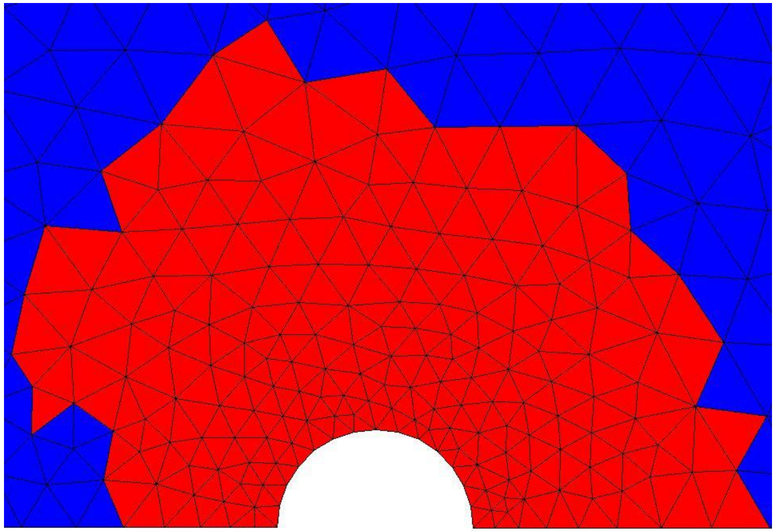
Drainage: Locations (red) of Particle Resuspension (Beheshti criteria)



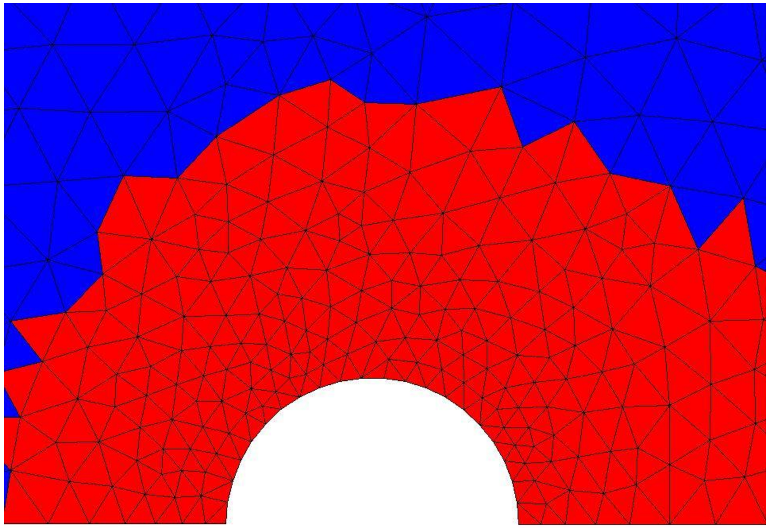
24 in center nozzle, high flow rate



24 in center nozzle, low flow rate



24 in near-wall nozzle, high flow rate



36 in near-wall nozzle, high flow rate

Extended Nozzle Analysis

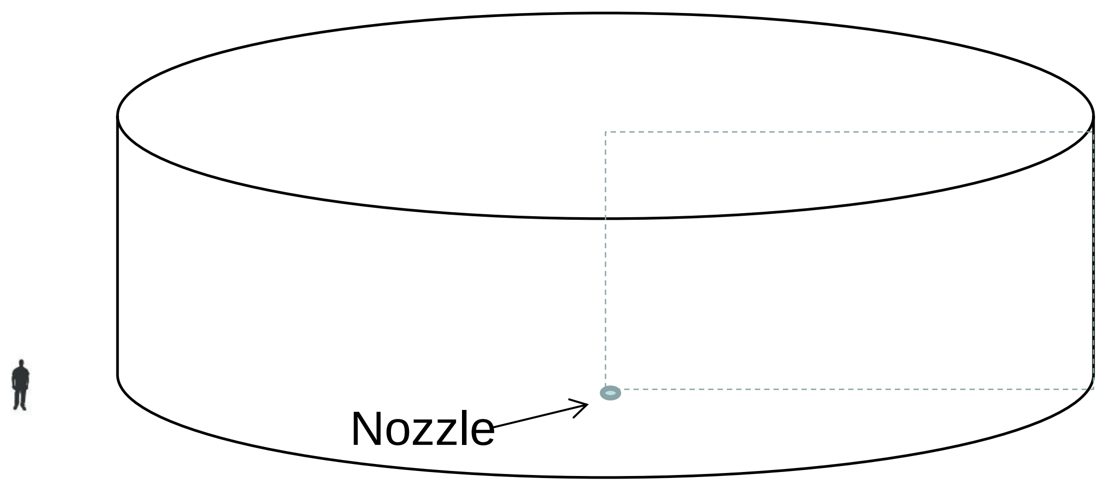
Objective

- Perform simulations with extended pipe (nozzle) above inlet/outlet to see if it reduces shear stress and particle resuspension

Extended Nozzle Analysis

- 2D axisymmetric domain (center nozzle)
- Two-phase volume-of-fluid model
- k-ω-sst turbulence model
- 1 mm, 0.1 mm, and 0.01 mm Particle sizes with uniform distribution
- 8239 elements
- Courant number ≈ 1
- **Center nozzle extended 6, 12, and 24 inches from bottom of tank**
- **Center nozzle wall thickness varied from 1, 2, and 3 inches (thickness did not have significant effect)**

Q = 0.631 m^3/s (10,000 GPM)

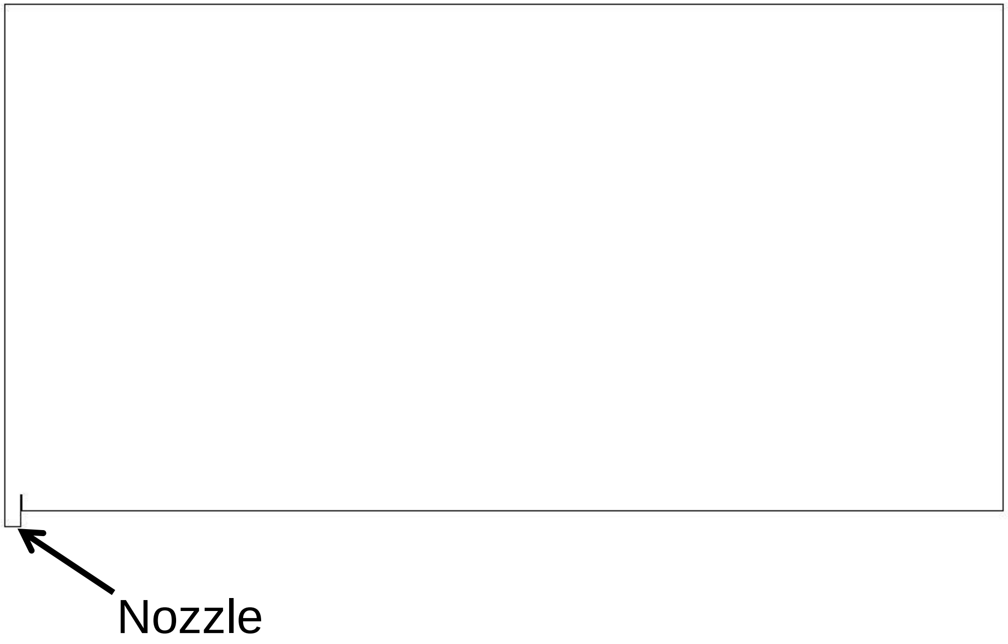


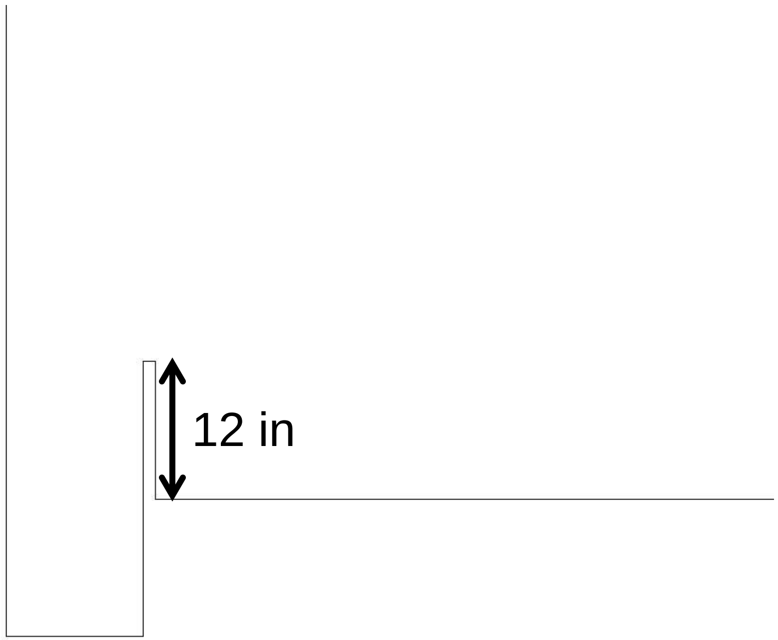
32’ height (initial water height = 16’)

24” nozzle diameter

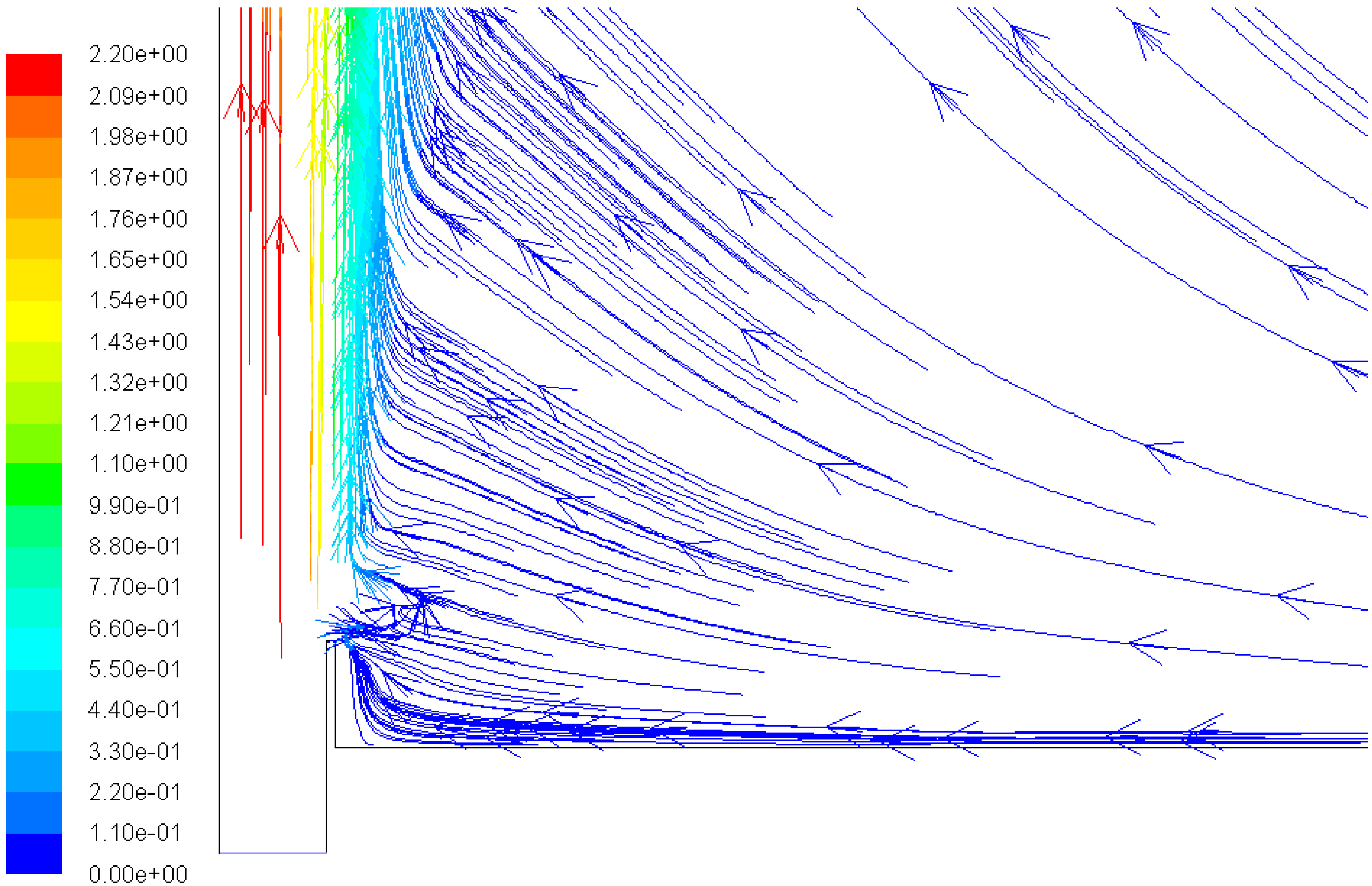
126’ diameter

Extended Nozzle Analysis – 12 in high, 1 in thick



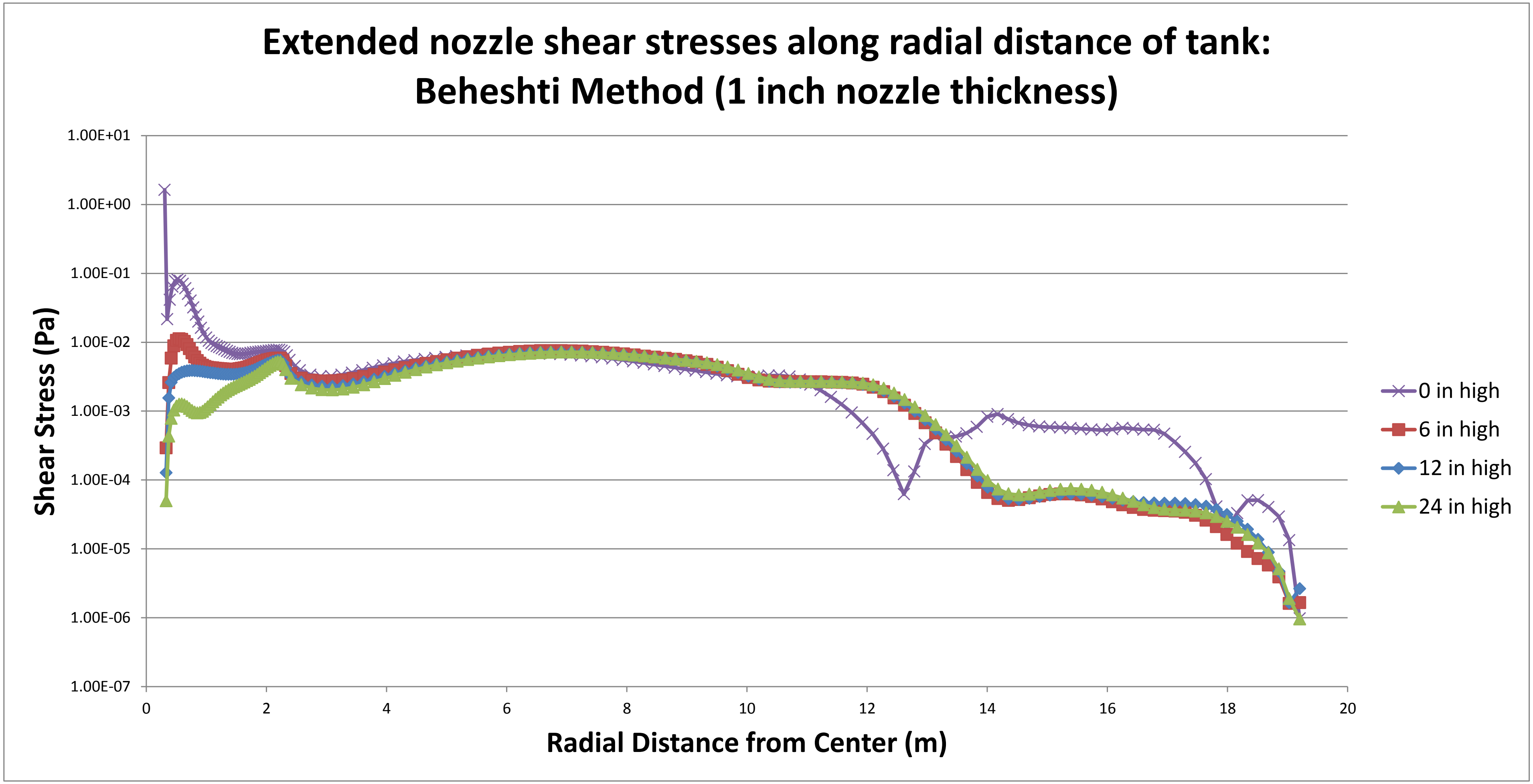


Extended Nozzle Analysis – Filling

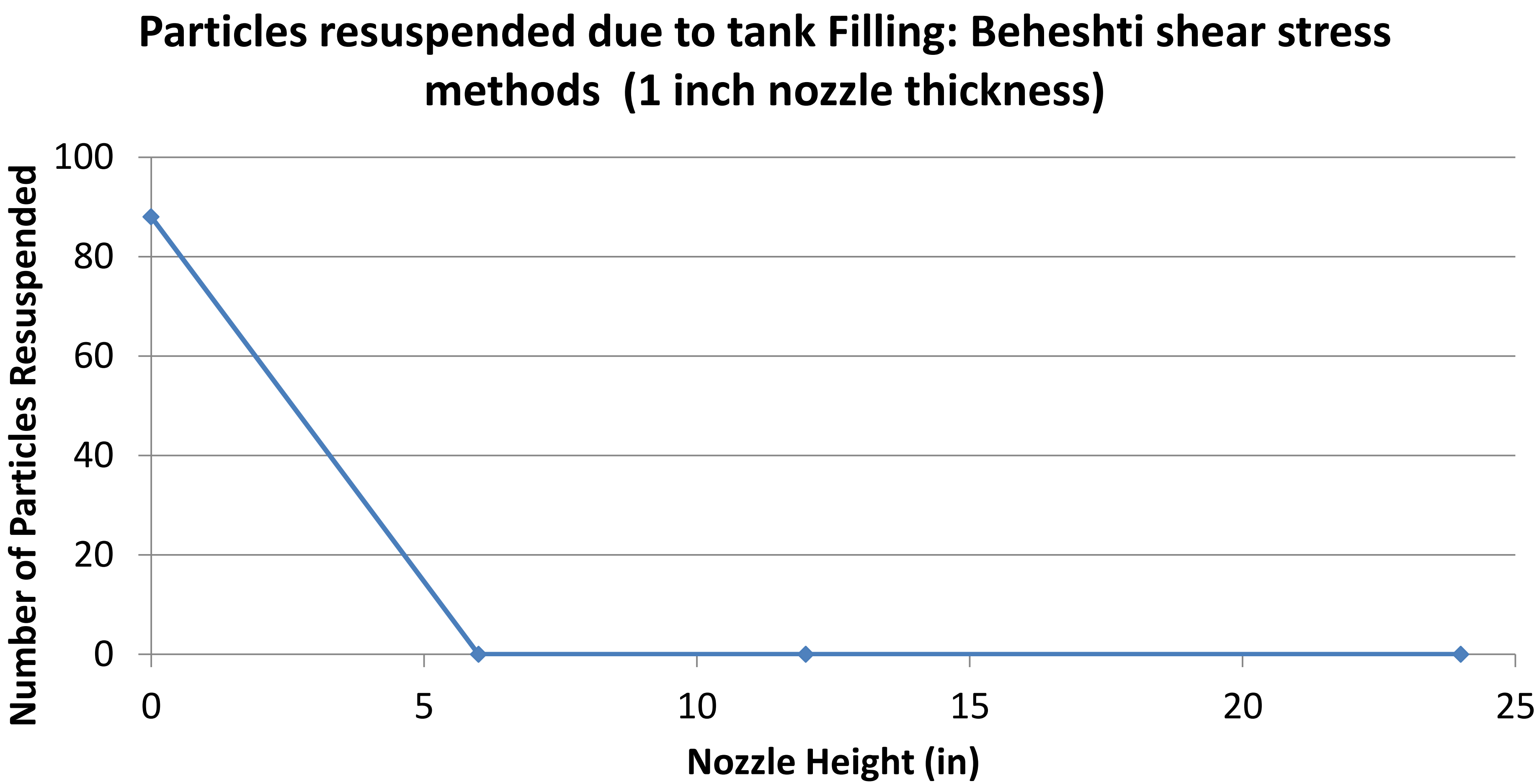


Pathlines Colored by Velocity Magnitude (mixture) (m/s) (Time=2.0000e+02) Oct 03, 2013
ANSYS Fluent 14.5 (axi, dp, pbns, vof, sstkw, transient)

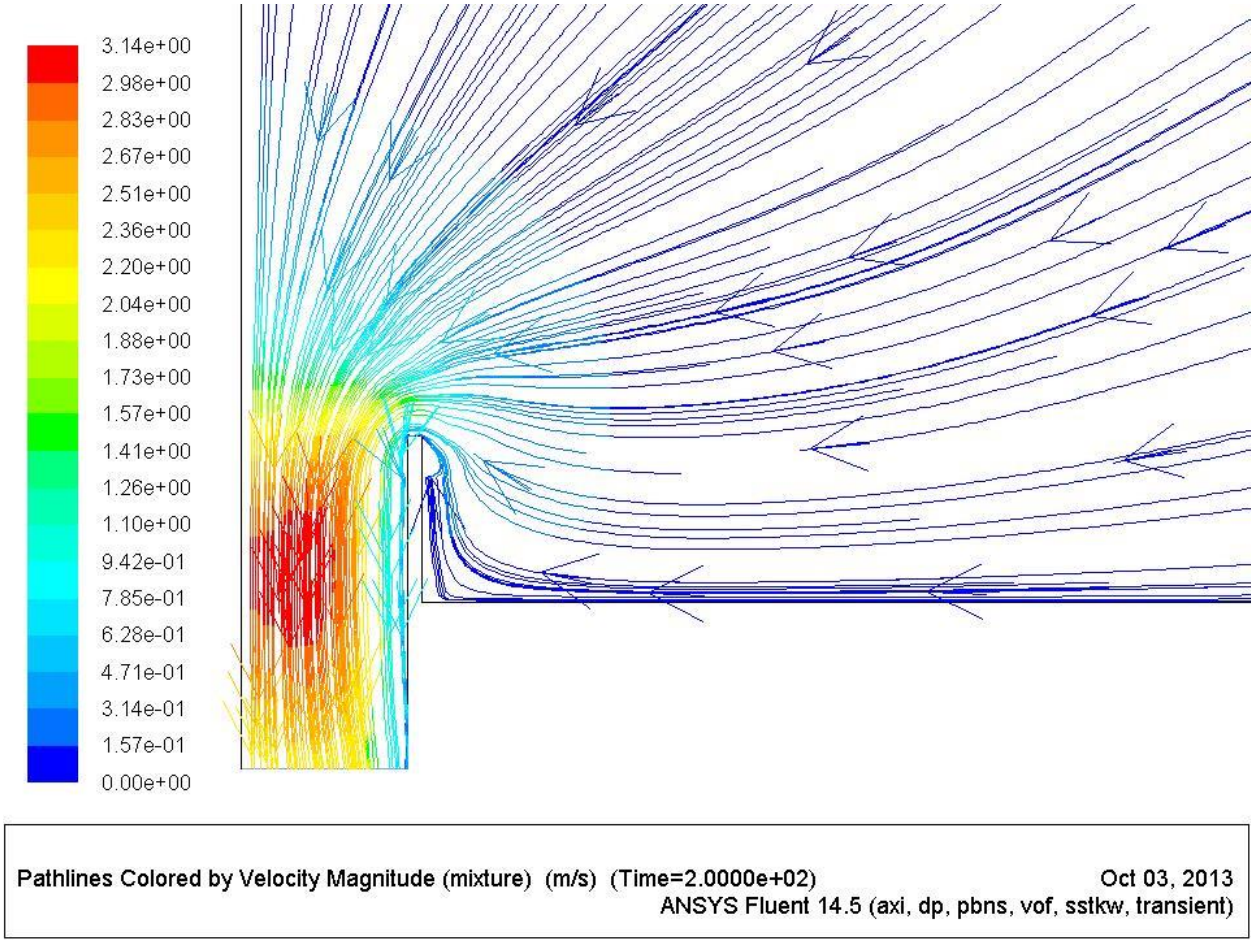
Extended Nozzle Analysis – Filling



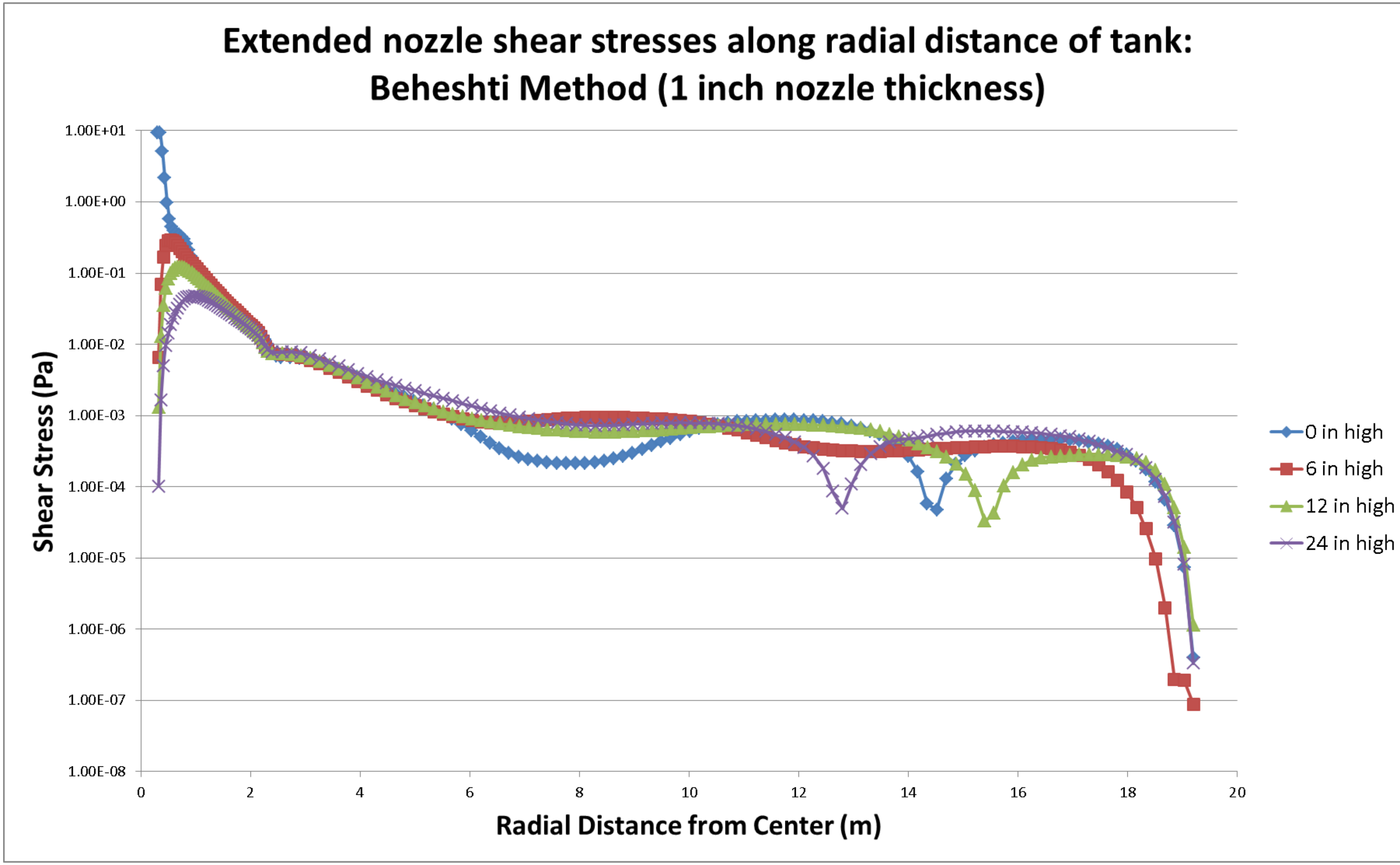
Extended Nozzle Analysis – Filling



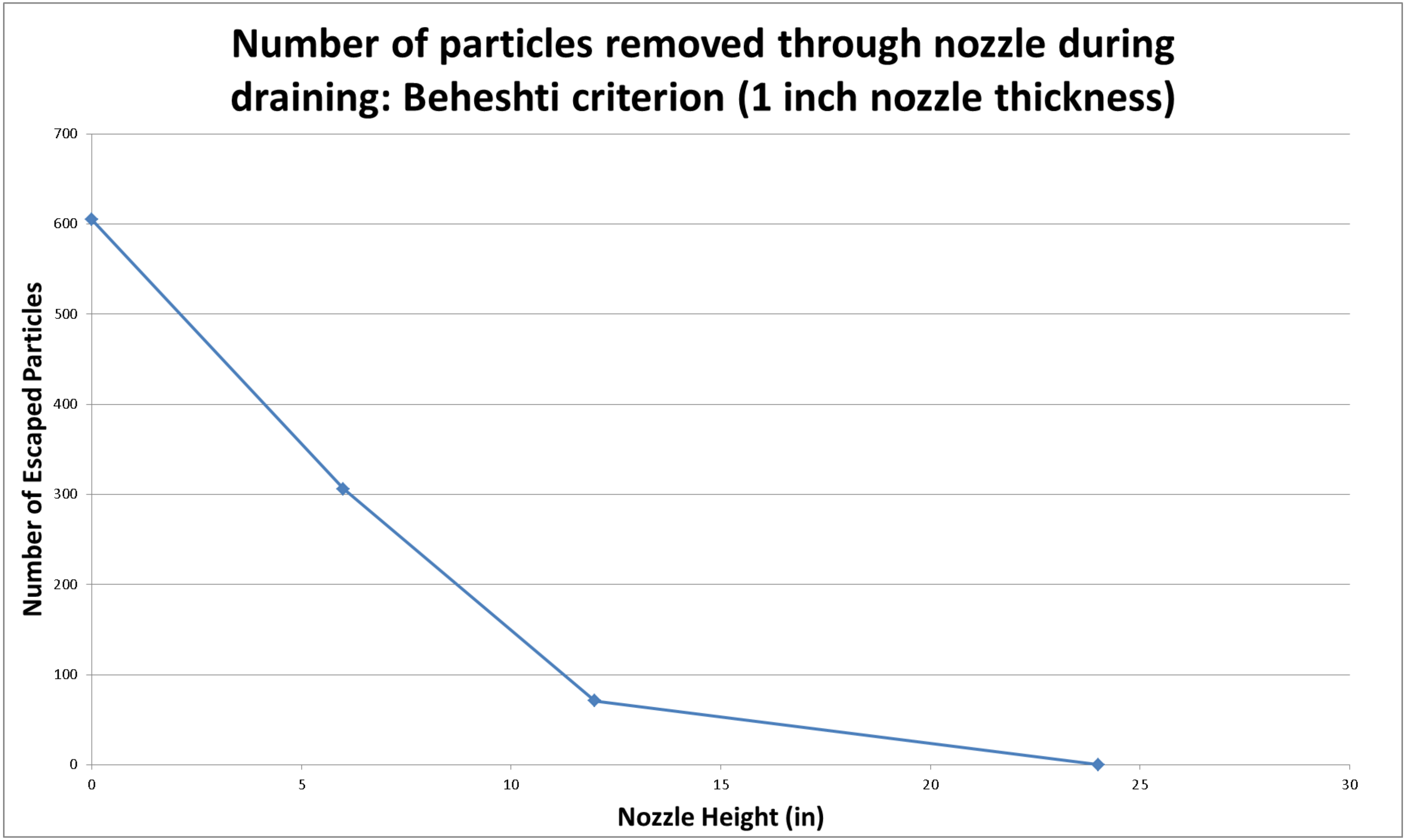
Extended Nozzle Analysis – Draining



Extended Nozzle Analysis - Draining



Extended Nozzle Analysis -- Draining



Overview

- Objectives and Background
- Modeling
- Testing
- Conclusions

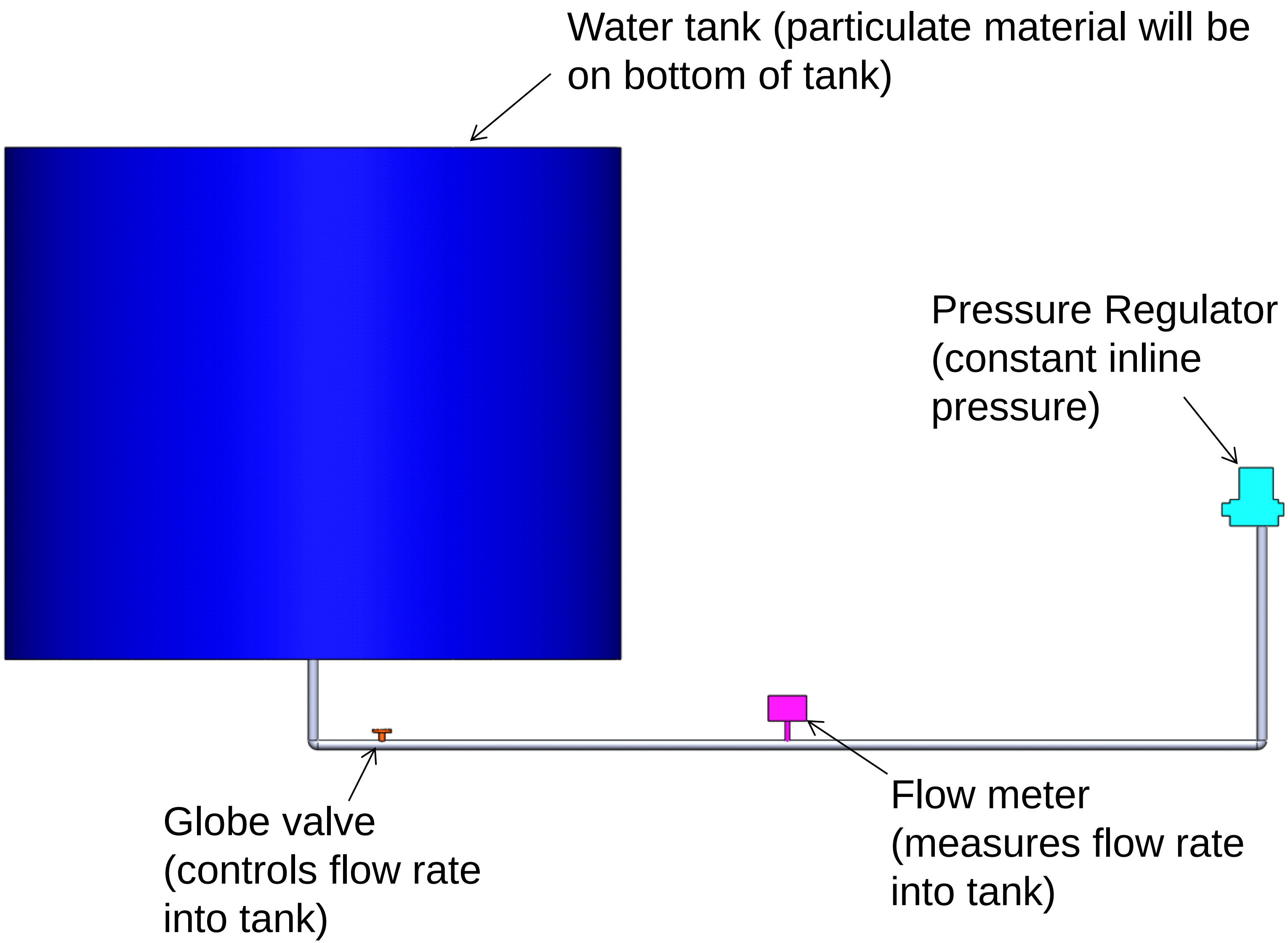
Test Objectives

- Perform small-scale tests to verify models and to observe particle resuspension during filling and draining

Experimental Plan

- Materials
  - Plastic tank (48 inch diameter)
  - Silica sand and glass beads (0.044 mm – 2 mm)
- Procedure
  - Measure velocities in tank with center nozzle location
  - Observe particle behavior (suspension and relocation)
  - Record extent of particle resuspension
  - Measure particle loss while draining
  - Vary flow rates and particle sizes

Experimental Setup



Experimental Components

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Large and small tanks

Flow meter

Pressure regulator

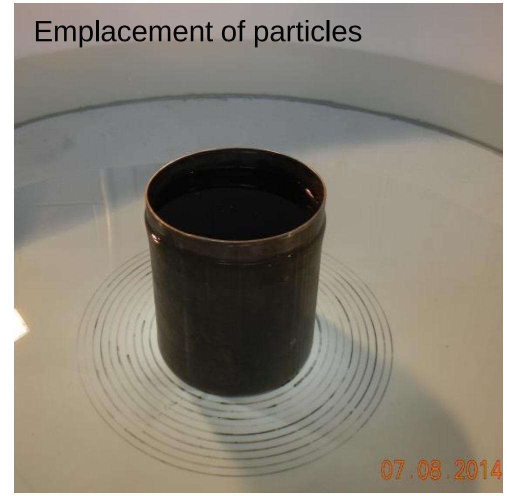
Valves

Velocity probe

Test parameters

- Performed filling and draining tests
  - Silica sand (50 – 100 microns or 1 – 2 mm)
    - Two sizes of sand
    - Filling only, draining only, fill/drain/fill/drain cycle
      - Two flow rates for filling
      - Gravity drainage
  - Glass beads
    - Two sizes of glass beads (1 mm or 2 mm)
    - Filling only, draining only, fill/drain/fill/drain cycles
      - Two flow rates for filling
      - Gravity drainage

Test Photos

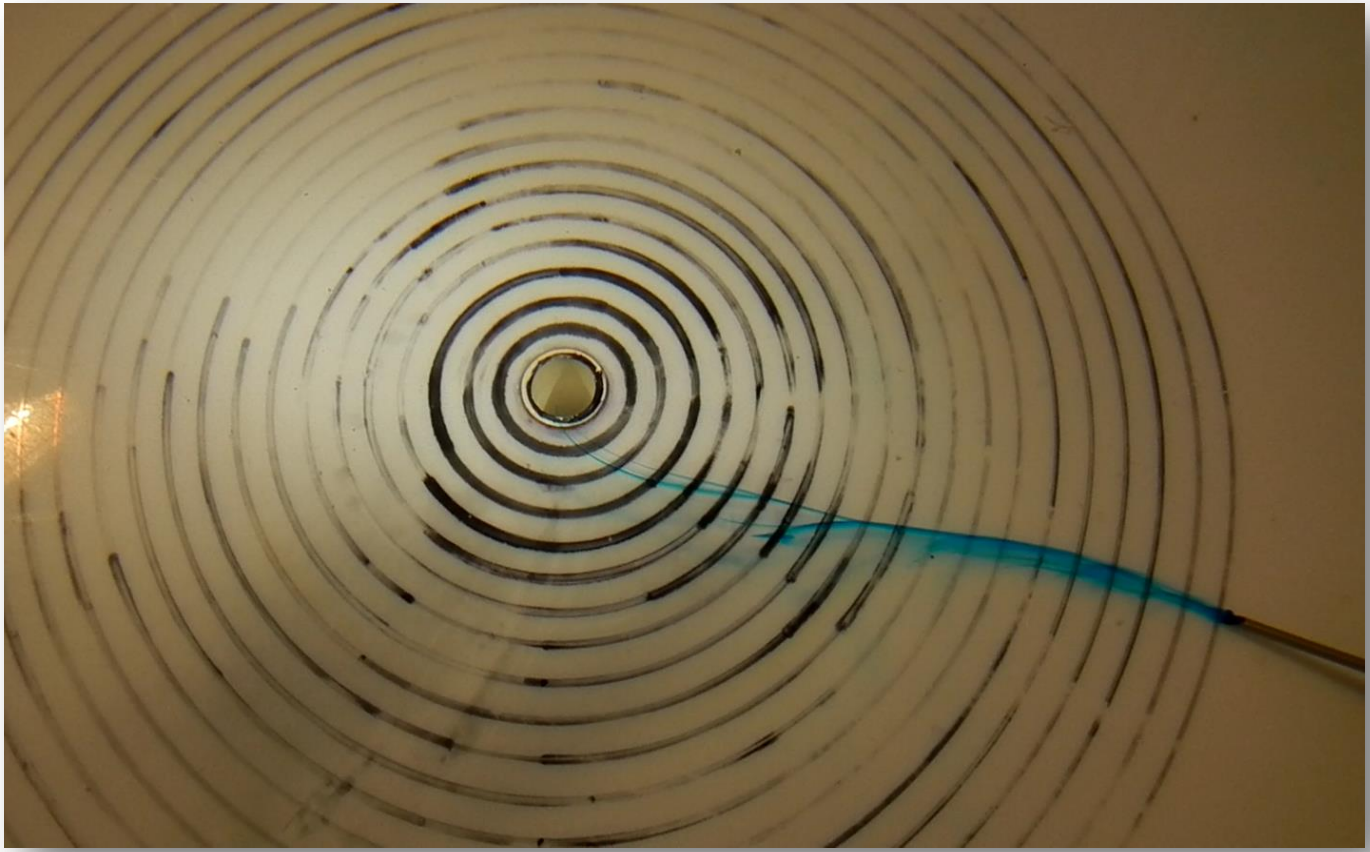


Emplacement of particles

Valves to divert flow from filling to draining

Flow that was drained was diverted through sieves for collection and weighing

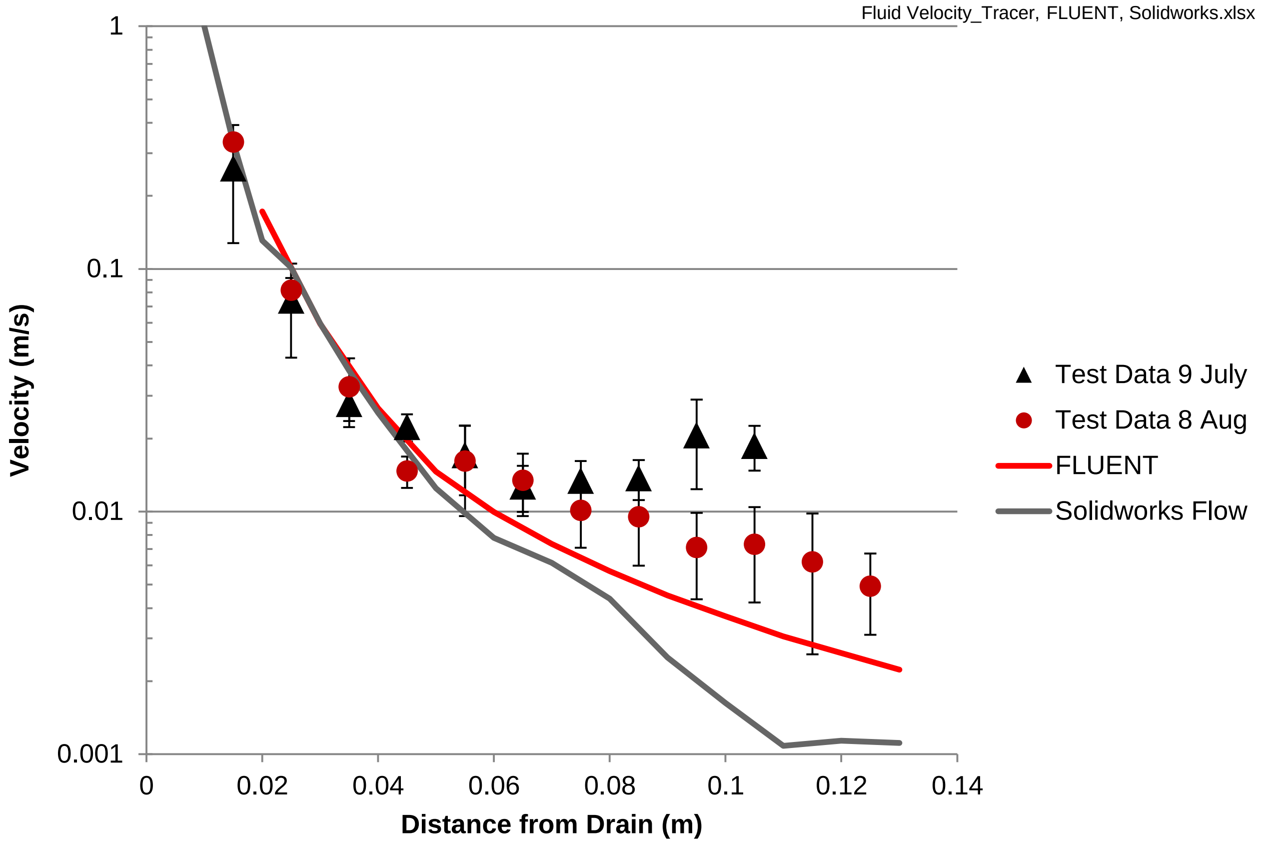
Tracer testing for velocity measurements



Velocity Comparison

(Model vs. Experiment)

Fluid velocity as a function of distance from drain center



Particle resuspension tests

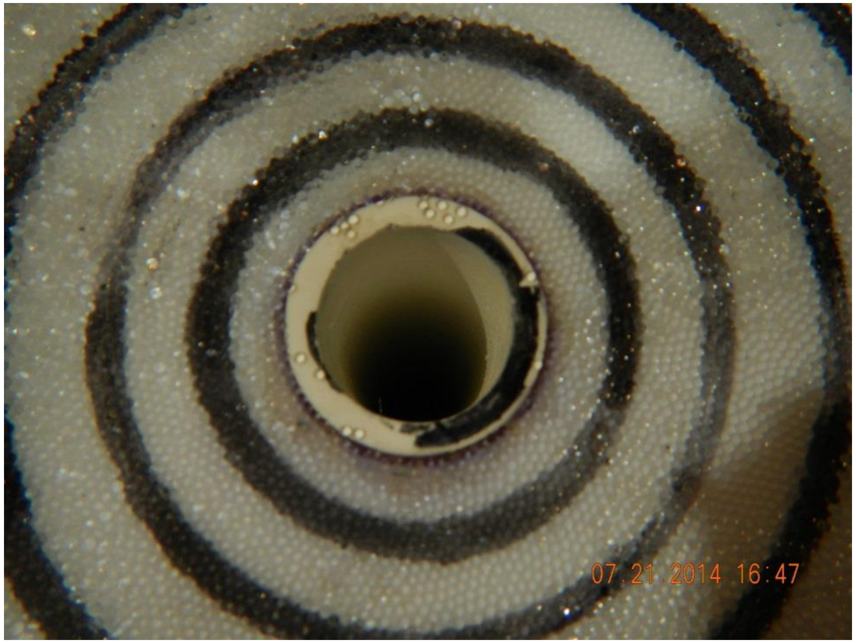
Draining – 0.853-1.68mm Silica Sand

Before Draining

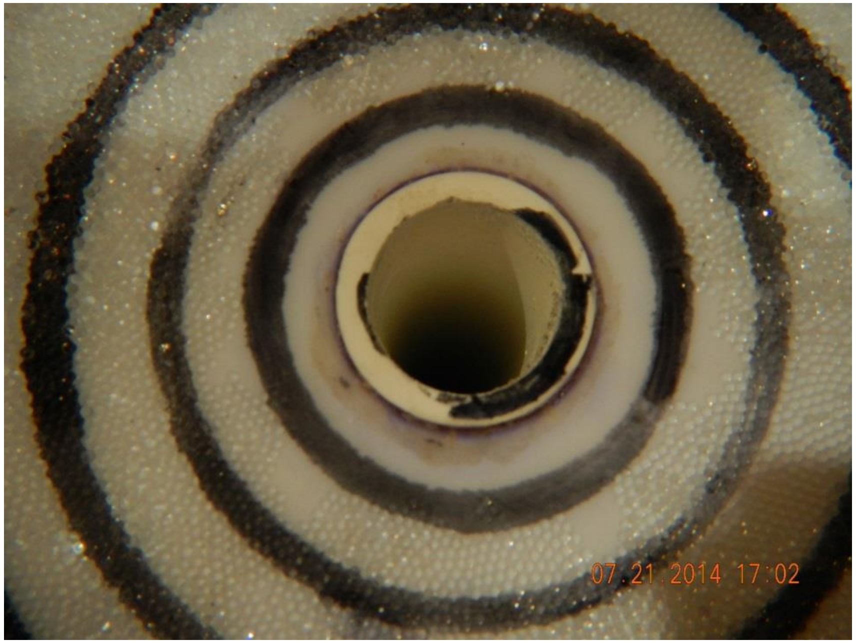
After Draining

Draining – 1mm Glass Beads

Before Draining



After Draining



Draining Results

Particle Type	Particle Density (kg/m^3)	Particle Diameter (mm)	Percent Collected during Draining (% by mass)	Average Radial Extent of Resuspension from Drain (cm)
Silica Sand	2650	0.053 – 0.104	4.17 ± 2.46	1.28 ± 0.06
Silica Sand	2650	0.853 – 1.68	2.79 ± 0.08	0.92 ± 0.07
Glass Beads	2450	1	4.20	1.51 ± 0.25
Glass Beads	2450	2	2.72	1.74 ± 0.26

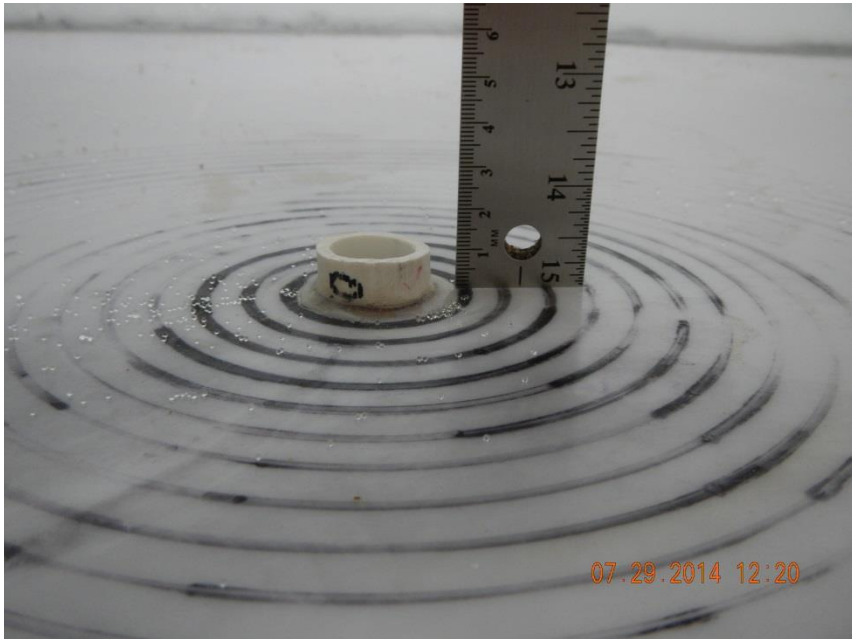
Note: Plus/minus corresponds to one standard deviation.

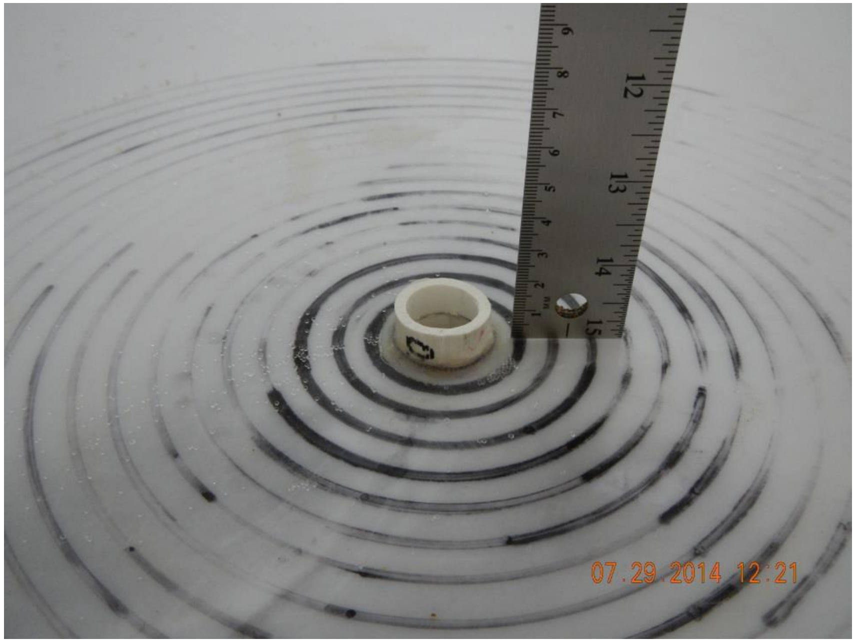
Filling Results

Particle	Particle Density (kg/m^3)	Particle Diameter (mm)	Fill Rate (m^3/s)	Average Radial Extent of Resuspension from Drain (cm)
Silica Sand	2650	0.053 – 0.104	1.96E-04	0.15 ± 0.05
Silica Sand	2650	0.053 – 0.104	4.01E-04	0.15 ± 0.05
Silica Sand	2650	0.853 – 1.68	1.92E-04	0.22 ± 0.11
Silica Sand	2650	0.853 – 1.68	3.65E-04	0.30
Glass Beads	2450	1	1.91E-04	0.44 ± 0.12
Glass Beads	2450	1	3.81E-04	0.50
Glass Beads	2450	2	1.92E-04	0.30
Glass Beads	2450	2	3.84E-04	0.30

Note: Plus/minus corresponds to one standard deviation.

Extended Nozzle





Extended Nozzle Draining – 0.853-1.68mm Silica Sand

Before Draining

After Draining

Extended Nozzle Draining – 1mm Glass Beads

Before Draining

After Draining

Fill, Drain, Fill, Drain Results

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Particle	Particle Density (kg/m^3)	Particle Diameter (mm)	Fill Rate (m^3/s)	Percent Collected during Draining (% by mass)	Average Radial Extent of Resuspension from Drain (cm)
Silica Sand	2650	0.053 – 0.104	1.91E-04	3.91 ± 0.51	1.36 ± 0.04
Silica Sand	2650	0.053 – 0.104	3.79E-04	5.53 ± 0.46	1.45 ± 0.13
Silica Sand	2650	0.853 – 1.68	1.89E-04	1.57	0.72 ± 0.15
Silica Sand	2650	0.853 – 1.68	3.66E-04	1.54	0.90 ± 0.19
Glass Beads	2450	1	1.89E-04	5.11	1.63 ± 0.30
Glass Beads	2450	1	3.85E-04	4.87	1.94 ± 0.29
Glass Beads	2450	2	1.93E-4	7.32 ± 0.19	1.83 ± 0.29
Glass Beads	2450	2	3.83E-04	5.76	1.90 ± 0.54

Note: Plus/minus corresponds to one standard deviation.

Extended Nozzle Results - Draining

Particle	Particle Density (kg/m^3)	Particle Diameter (mm)	Percent Collected during Draining (% by mass)	Average Radial Extent of Resuspension from Drain (cm)
Silica Sand	2650	0.053 – 0.104	0.55	No visible extent
Silica Sand	2650	0.853 – 1.68	0	0
Glass Beads	2450	2	0	0
Glass Beads	2450	1	0	0

Extended Nozzle Results - Filling

Particle	Particle Density (kg/m^3)	Particle Diameter (mm)	Fill Rate (m^3/s)	Average Radial Extent of Resuspension from Drain (cm)
Silica Sand	2650	0.053 – 0.104	1.94E-04	No visible extent
Silica Sand	2650	0.053 – 0.104	3.82E-04	No visible extent
Silica Sand	2650	0.853 – 1.68	1.96E-04	No visible extent
Silica Sand	2650	0.853 – 1.68	3.82E-04	No visible extent
Glass Beads	2450	1	1.94E-04	No visible extent
Glass Beads	2450	1	3.79E-04	No visible extent
Glass Beads	2450	2	1.92E-04	No visible extent
Glass Beads	2450	2	3.79E-04	No visible extent

Particle Resuspension Summary and Comparison with Models

Particle	Particle Diameter (mm)	Test Type	Modeled Radial Extent of Particle Resuspension from Edge of Inlet/Drain (cm)		Experimental Radial Extent of Particle Resuspension from Edge of Inlet/Drain (cm)
			Shields Model	Beheshti Model	
Silica Sand	0.053-0.104	Draining	2.48 - 3.70	1.95 - 2.48	1.28 ± 0.06
Silica Sand	0.853-1.68	Draining	1.34 - 1.60	1. 34 - 1.60	0.92 ± 0.07
Silica Sand	0.053-0.104	High Fill, Drain	2.48 - 3.70	1.95 - 2.48	1.45 ± 0.13
Silica Sand	0.853-1.68	High Fill, Drain	1.34 - 1.60	1. 34 - 1.60	0.90 ± 0.19
Silica Sand	0.053-0.104	Low Fill, Drain	2.48 - 3.70	1.95 - 2.48	1.36 ± 0.04
Silica Sand	0.853-1.68	Low Fill, Drain	1.34 - 1.60	1. 34 - 1.60	0.72 ± 0.15
Glass Beads	1	Draining	1.34-1.60	1.34-1.60	1.51 ± 0.25
Glass Beads	2	Draining	1.08-1.34	1.08-1.34	1.74 ± 0.26
Glass Beads	1	High Fill, Drain	1.34-1.60	1.34-1.60	1.94 ± 0.29
Glass Beads	2	High Fill, Drain	1.08-1.34	1.08-1.34	1.90 ± 0.54
Glass Beads	1	Low Fill, Drain	1.34-1.60	1.34-1.60	1.63 ± 0.30
Glass Beads	2	Low Fill, Drain	1.08-1.34	1.08-1.34	1.83 ± 0.29

Conclusions

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- Parametric studies were performed to determine importance of various factors on particle resuspension during filling and draining
  - Filling
    - Particle size, particle flow rate, and inlet location were important factors
      - Smaller particles (0.01 mm) were more susceptible to resuspension
        - Near-wall inlet yielded more resuspension
        - Higher flow rates yielded more resuspension
  - Draining
    - Flow rate and particle size were important factors
      - Smaller particles were more susceptible to resuspension, although the difference was less during draining than filling
      - In general, a larger percentage of particles was resuspended during draining vs. filling

Conclusions

- Operational study was performed to evaluate particle movement during filling and draining cycles
  - Particle resuspension from tank bottom generally occurred immediately following start of either fillling or draining event
  - Entrainment of particles during filling typically carried particles further away from the inlet/outlet, making them less susceptible
  - Smaller particles (0.01 mm) were more susceptible to resuspension and entrainment
  - Recirculation zones of particles near the inlet/outlet were observed
  - Greater shear stress during draining led to more particle resuspension than during filling

Conclusions

- Testing was performed to build confidence in the models
  - Measured and simulated velocities along tank bottom matched well up to ~5 cm from drain
    - This includes region where particles were resuspended
  - Measured and simulated radial extent of particle resuspension
    - Model predictions generally matched experimental data for glass beads
    - Models generally over predicted particle resuspension with silica sand
      - Possibly due to non-spherical shape of actual particles which resisted movement

Conclusions

- Both modeling and experiments showed that an extended pipe (nozzle) above the inlet/outlet mitigated particle resuspension during both filling and draining
  - Minimum height of the extension to completely mitigate particle movement near the inlet/outlet was found to be about 3 - 8% of the head of water
    - In the tests, an extension of 1 cm (0.39”) mitigated particle movement with a maximum head of water of 30 cm (12”)
    - In the models, an extension of ~0.38 m (1.3 ft) mitigated particle movement with a head of water of 4.9 m (16 ft)