CFD Methods for Evaluating Air Entrainment in Drop Structures

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for

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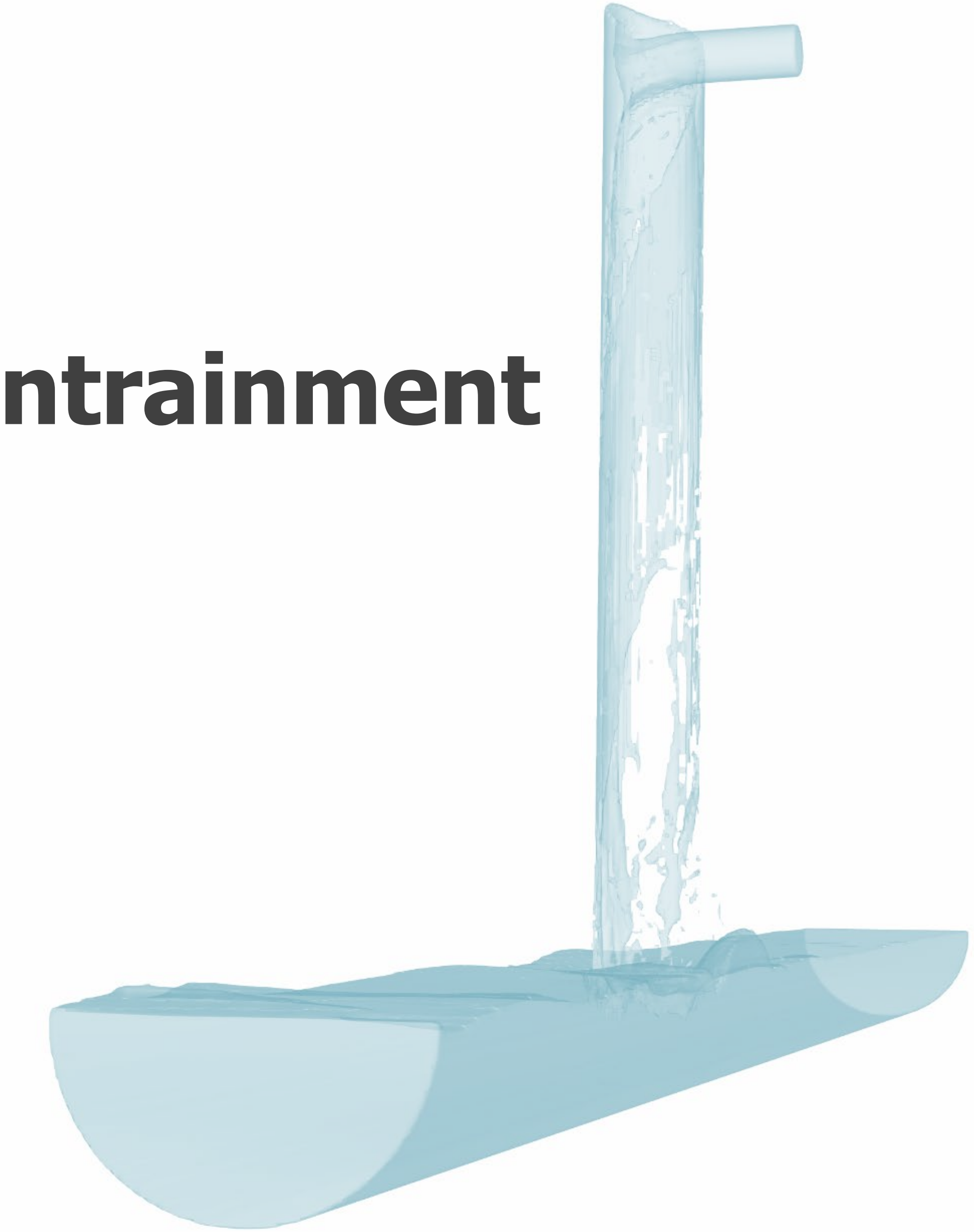


Outline

- Drop Structures: Key Design Considerations
- CFD Modeling
  - VOF method (free surface flows)
  - Air entrainment model
- Modeling dropshafts

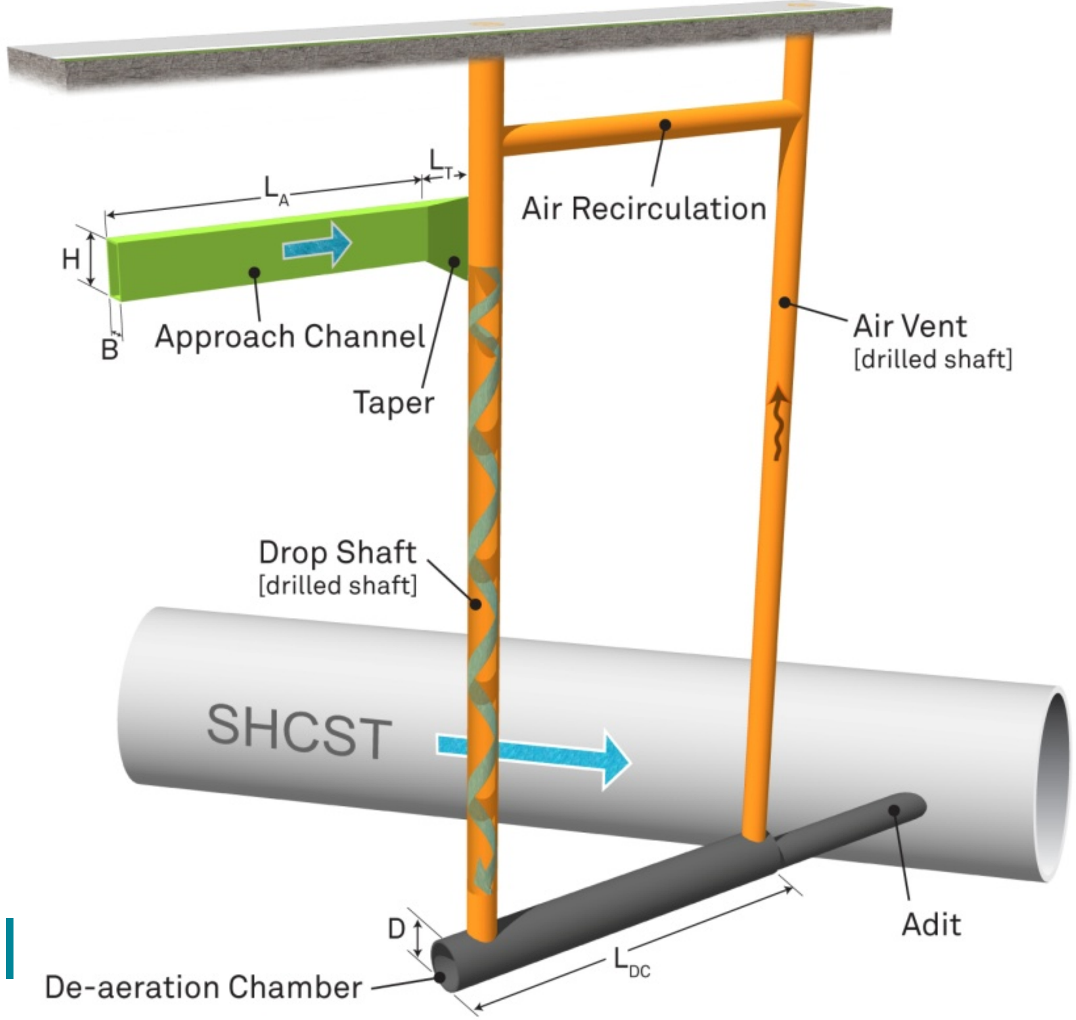
Drop Structure Design

Key Design Objectives

- *Dissipate energy from the flow*
- *Minimize air entrained and transported into the main tunnel*

Considerations

- General inlet configuration (vortex/plunge)
- System hydraulics, venting and odor control
- Constructability
- Maintenance



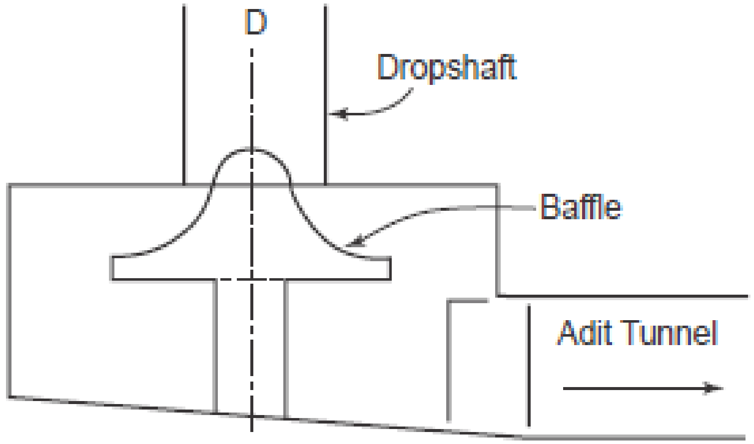
Components of a Vortex Drop Structure
(Image Courtesy: AECOM)

Edison, R., Design of a Tangential Vortex Drop Structure Using FLOW-3D, World Users Conference, 2012

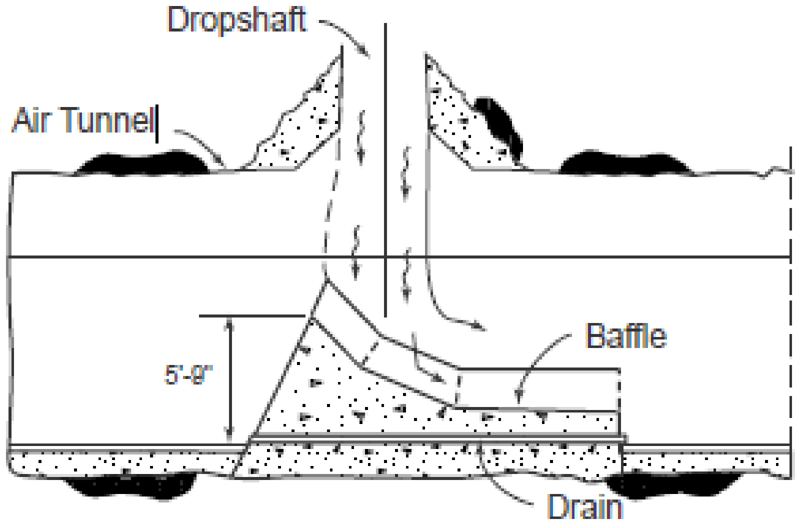
Drop Structure Design

Key Design Objectives

- *Dissipate energy from the flow*
- *Minimize air entrained and transported into the main tunnel*

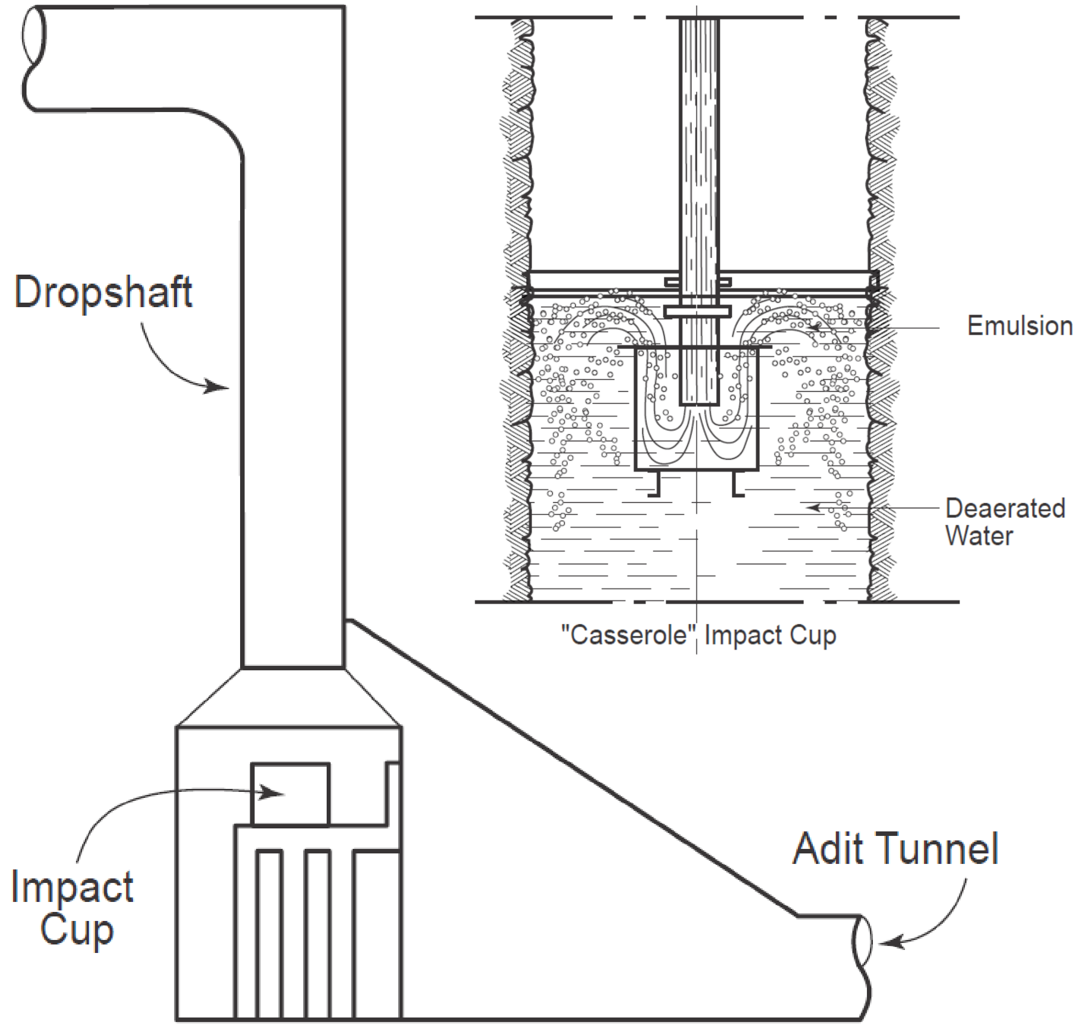


Baffle at the Base of a Plunge-Flow Drop Structure



Deflector Baffle at the Base of a Plunge-Flow Drop Structure

Baffles and deflectors in plunge flow drop structures

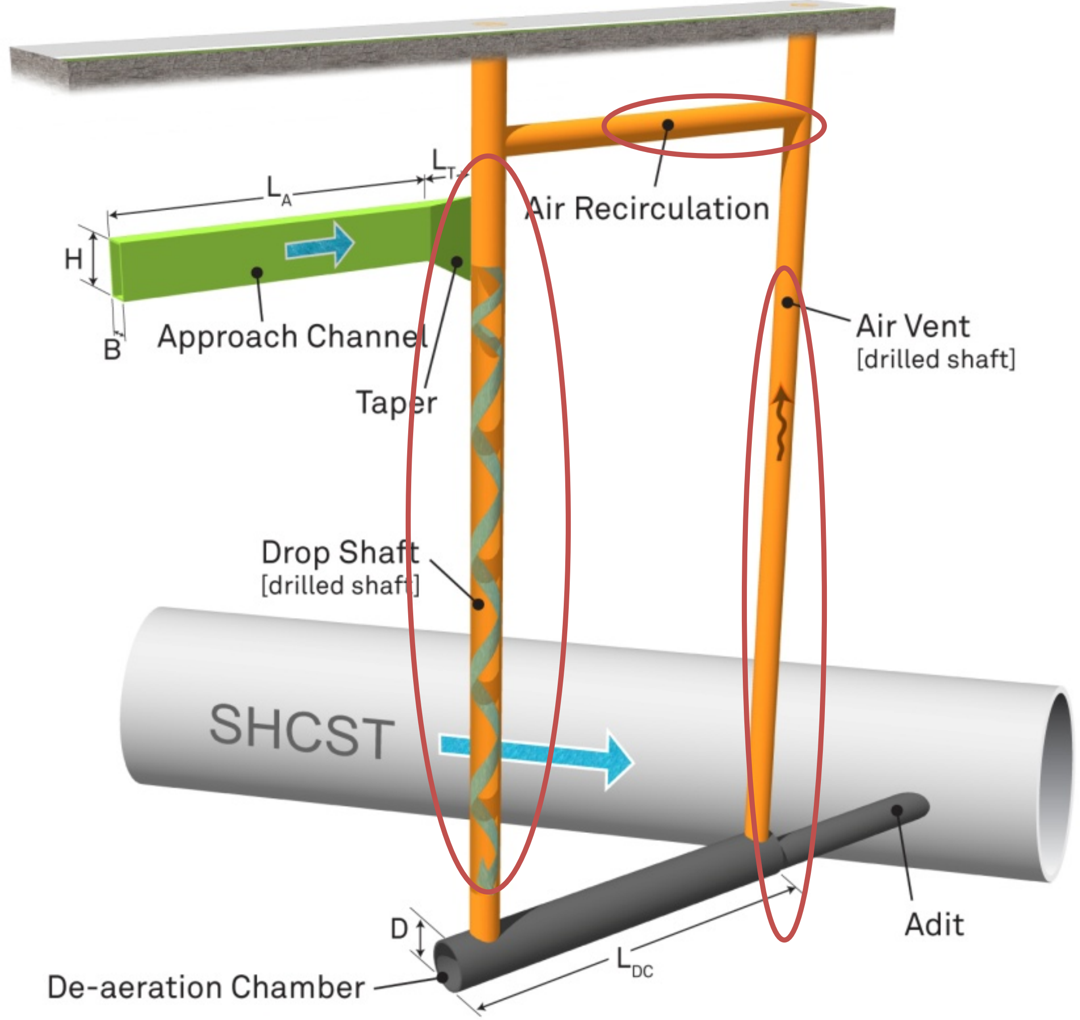


Impact Cup + plunge pool
(Images from Williamson, 2001)

Drop Structure Design

Key Design Objectives

- *Dissipate energy from the flow*
- *Minimize air entrained and transported into the main tunnel*
  - Good hydraulic design
  - Sufficient venting
  - Air management inside the system



Components of a Vortex Drop Structure
(Image Courtesy: AECOM)

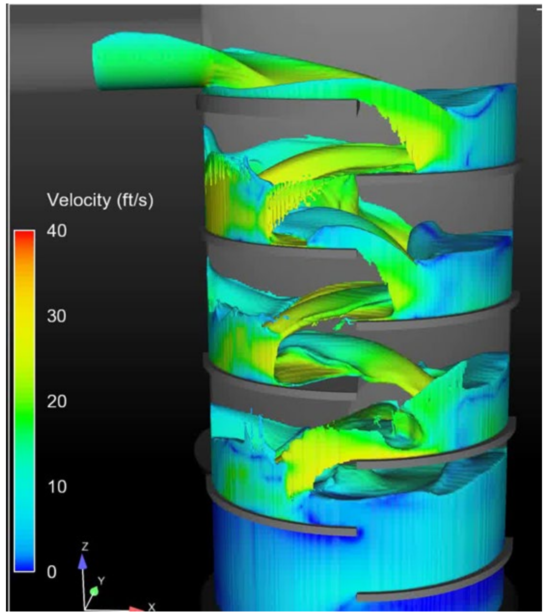
Where can 3D CFD modeling help?

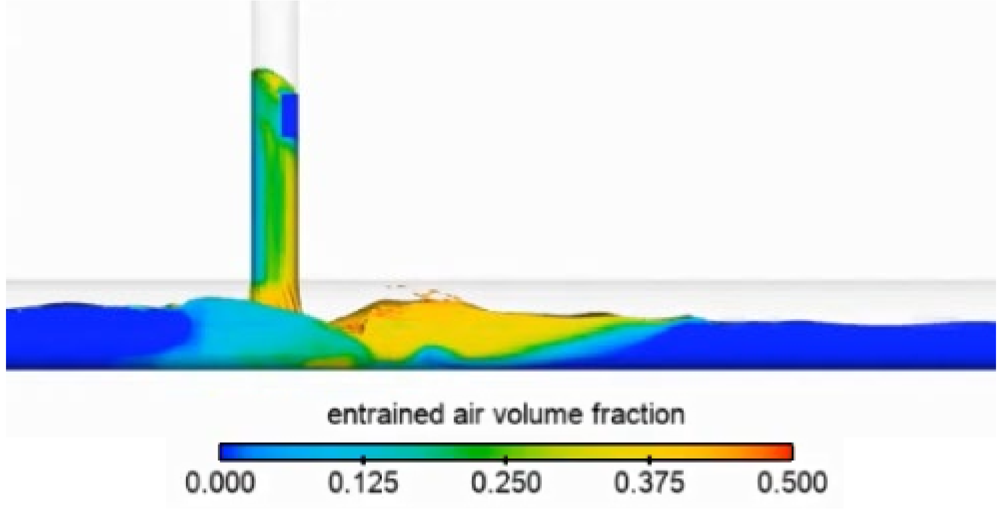
Key Design Objectives

- ✓ *Dissipate energy from the flow*
- ✓ *Minimize air entrained and transported into the main tunnel*

Considerations

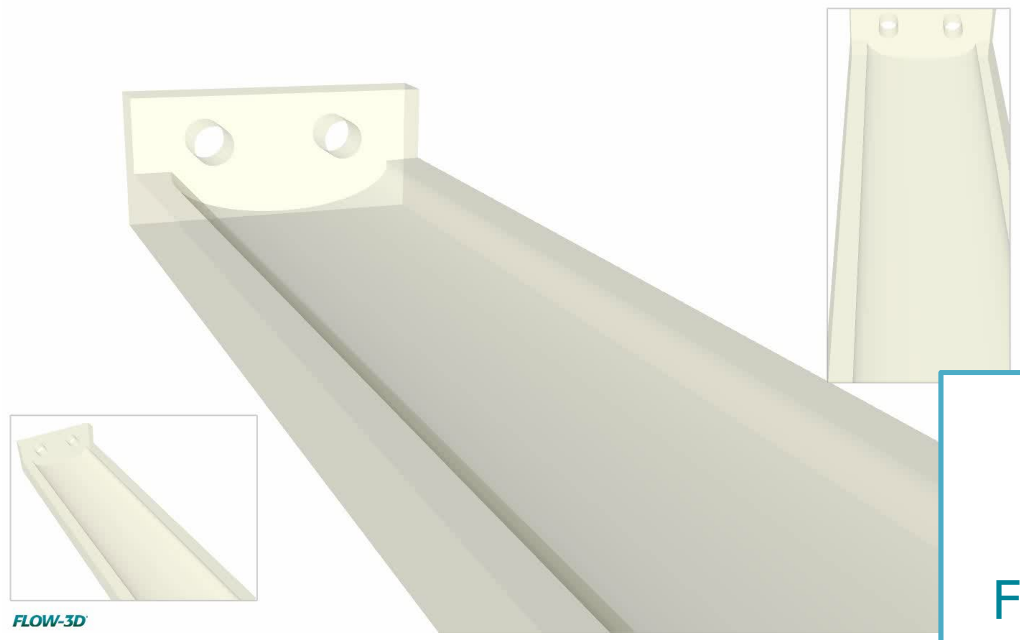
- ✓ *General inlet configuration (vortex/plunge)*
- ✓ *System hydraulics and venting*
- Constructability
- Maintenance

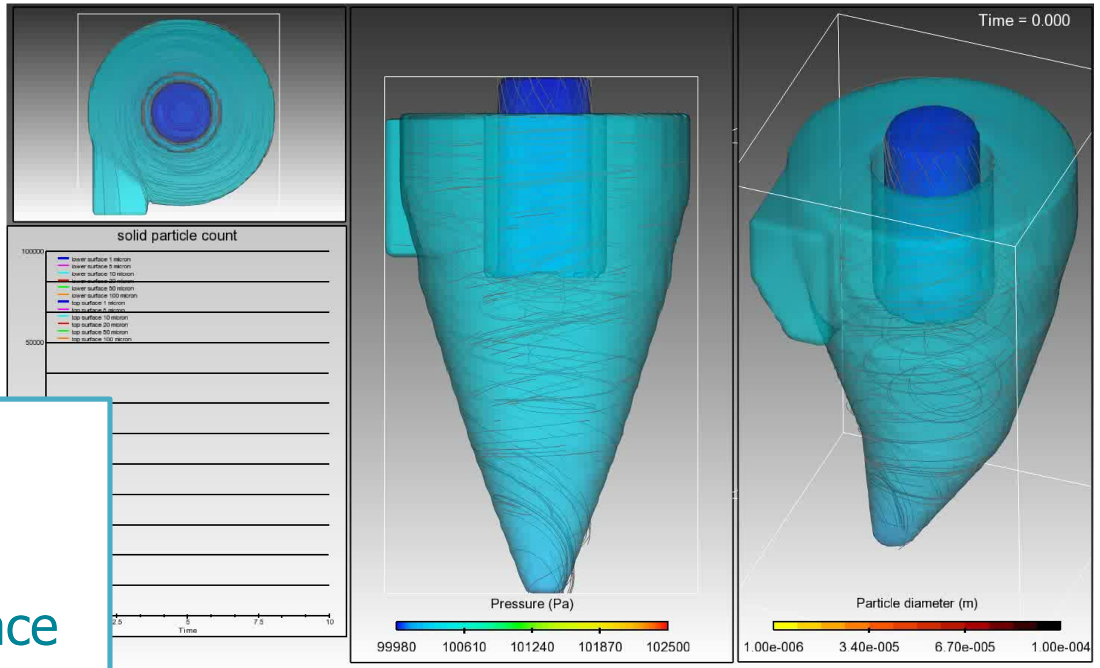




a. Energy dissipation means lowered velocities as water leaves the shaft; b. location and transport of entrained air in the system

Where is CFD effective?





Free Surface Flows

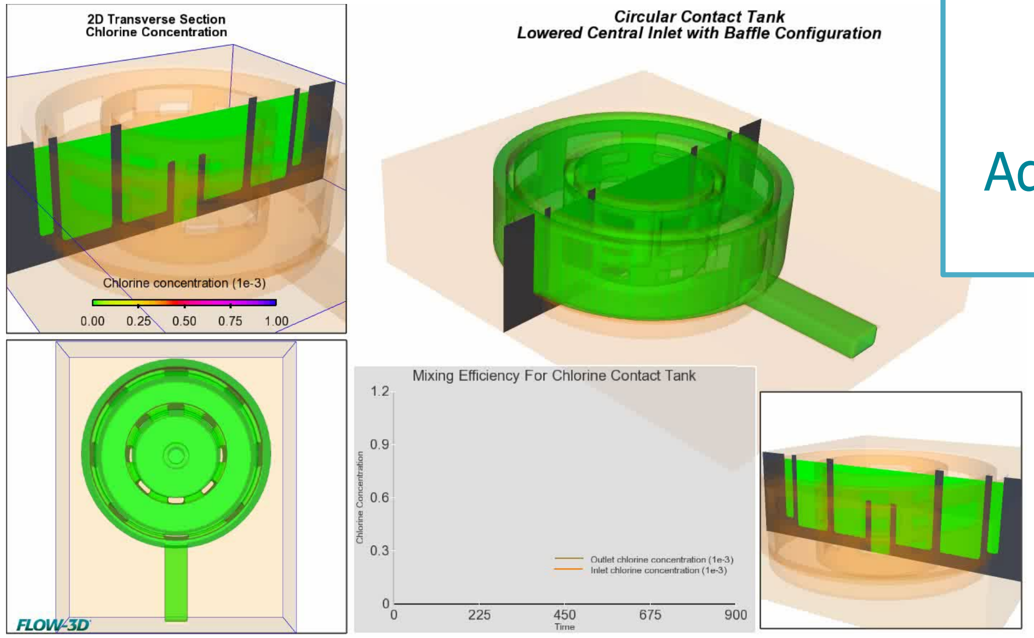
Fluid-gas / fluid-fluid interface

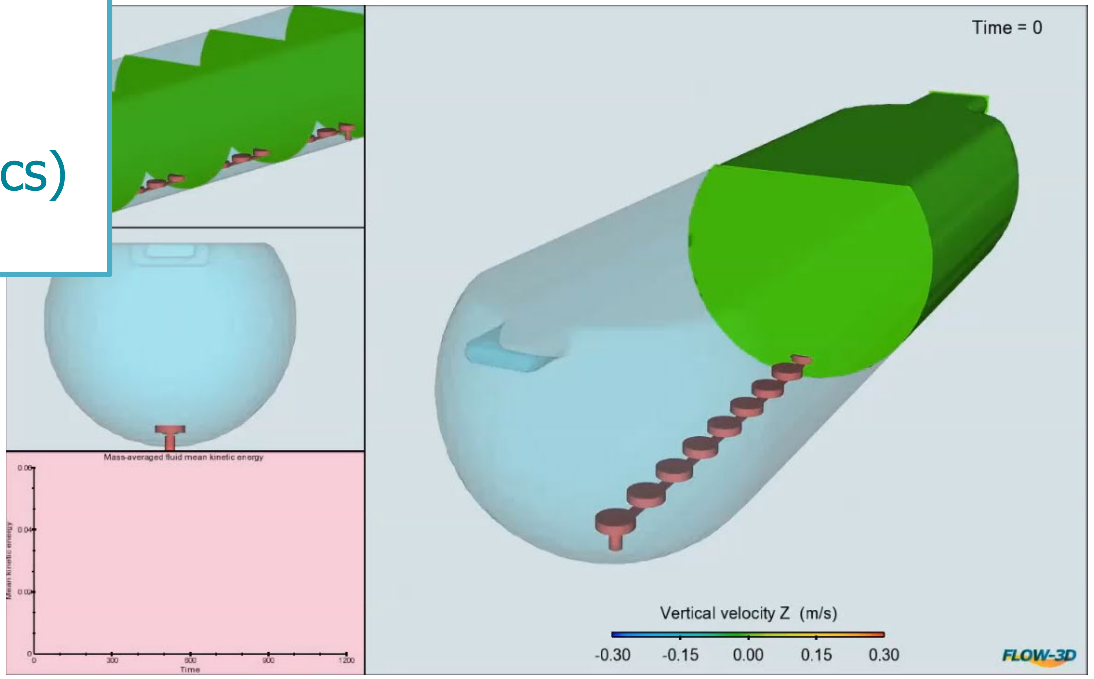
3-Dimensional

Transient

Complex

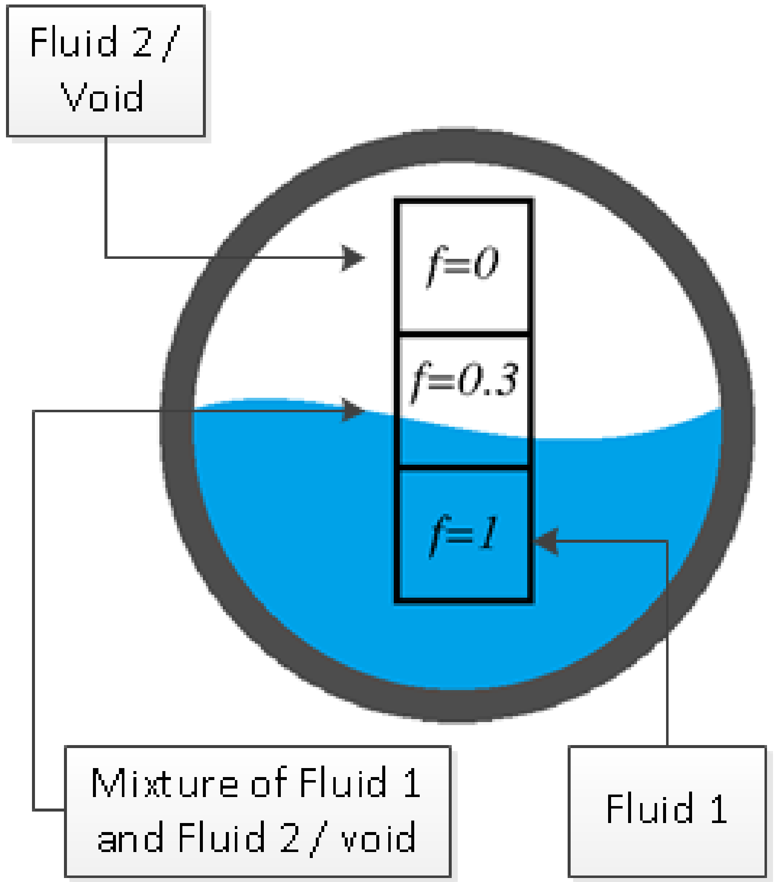
Additional complexity (physics)





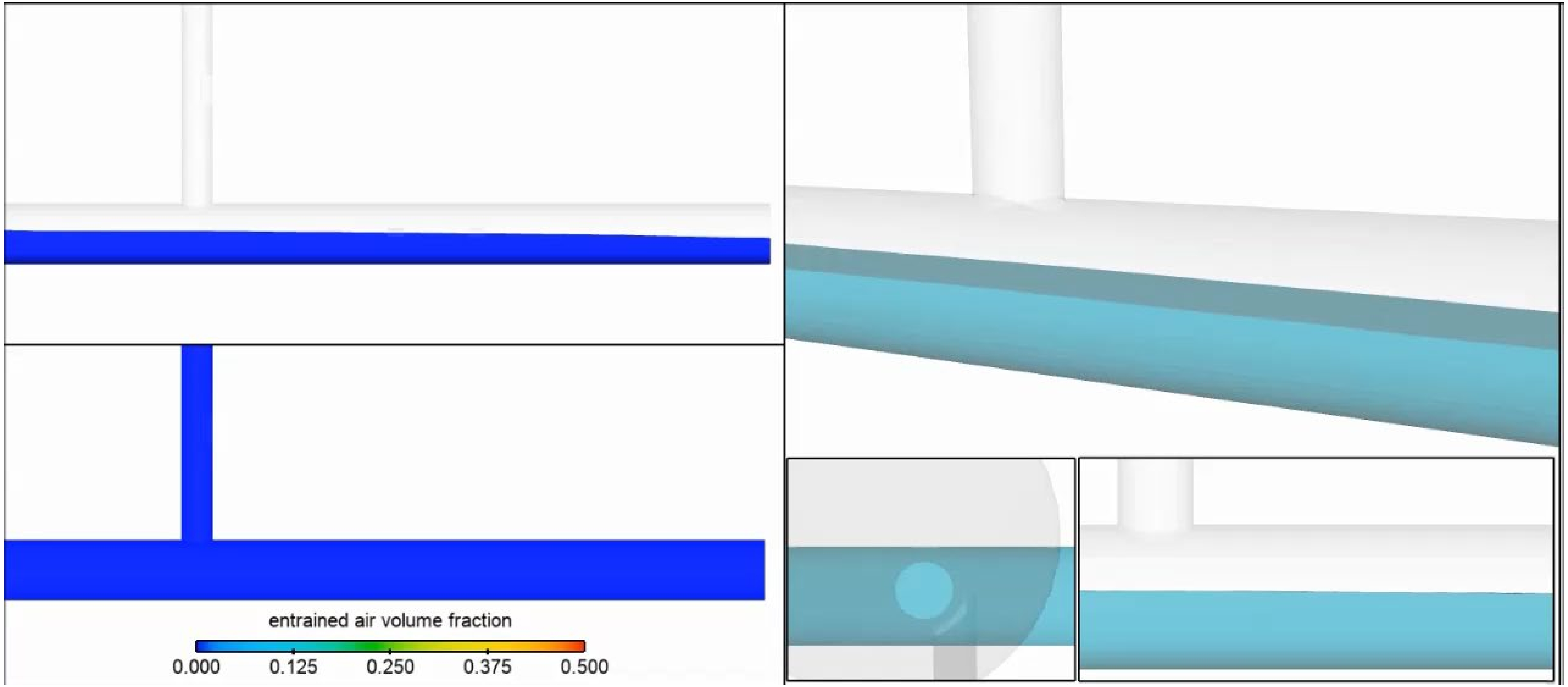
Volume of Fluid (VOF)

- VOF: Method for tracking the free surface
  - Locate the surface
  - Track the surface as a sharp interface within the mesh
  - Apply a boundary condition to the free surface
- 1 Fluid VOF (voids) vs. 2 Fluid VOF approach
  - Voids are regions of uniform properties that provide a boundary condition at the free surface
  - All governing equations are solved for fluid 2 (computationally more intensive)



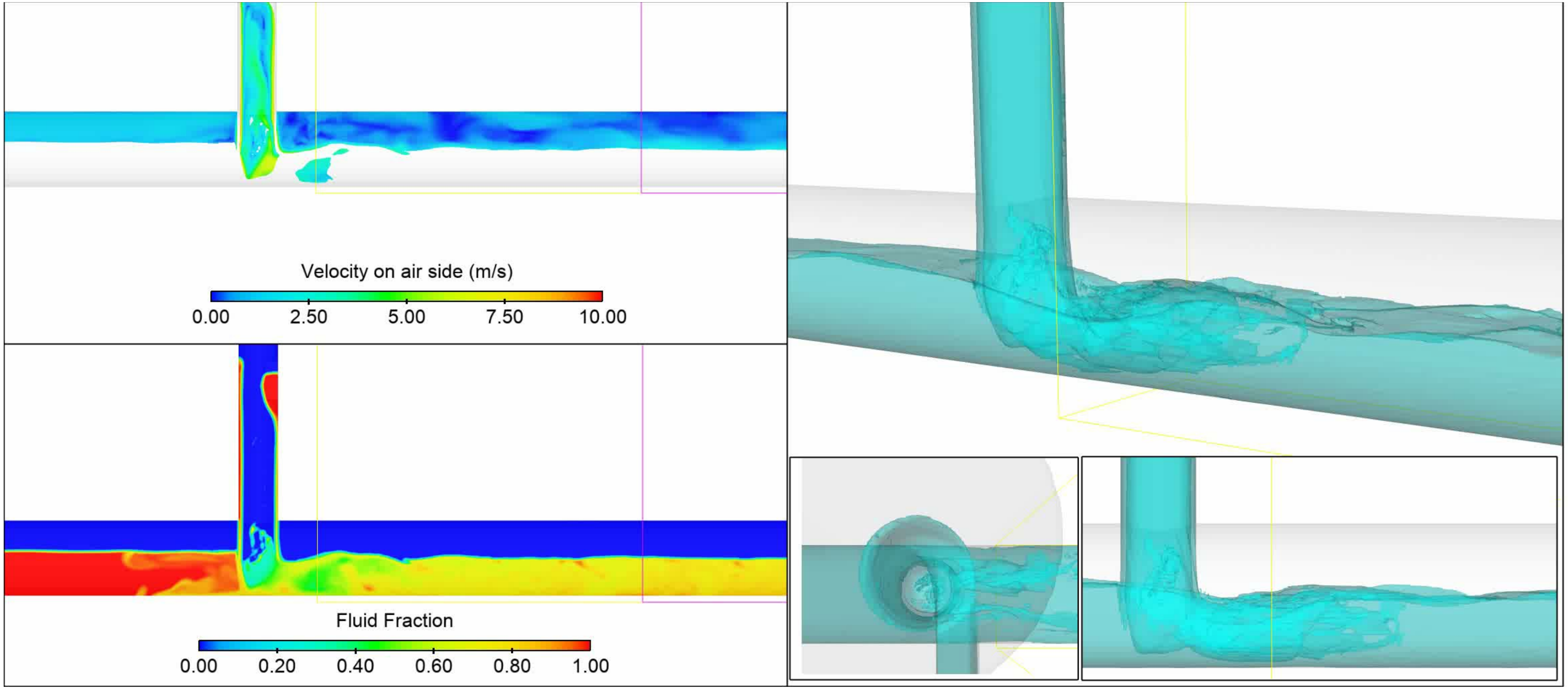
https://www.flow3d.com/resources/cfd-101/modeling-techniques/vof-whats-in-a-name/

VOF methods: Drop Structure



1-fluid VOF model of a tangential dropshaft

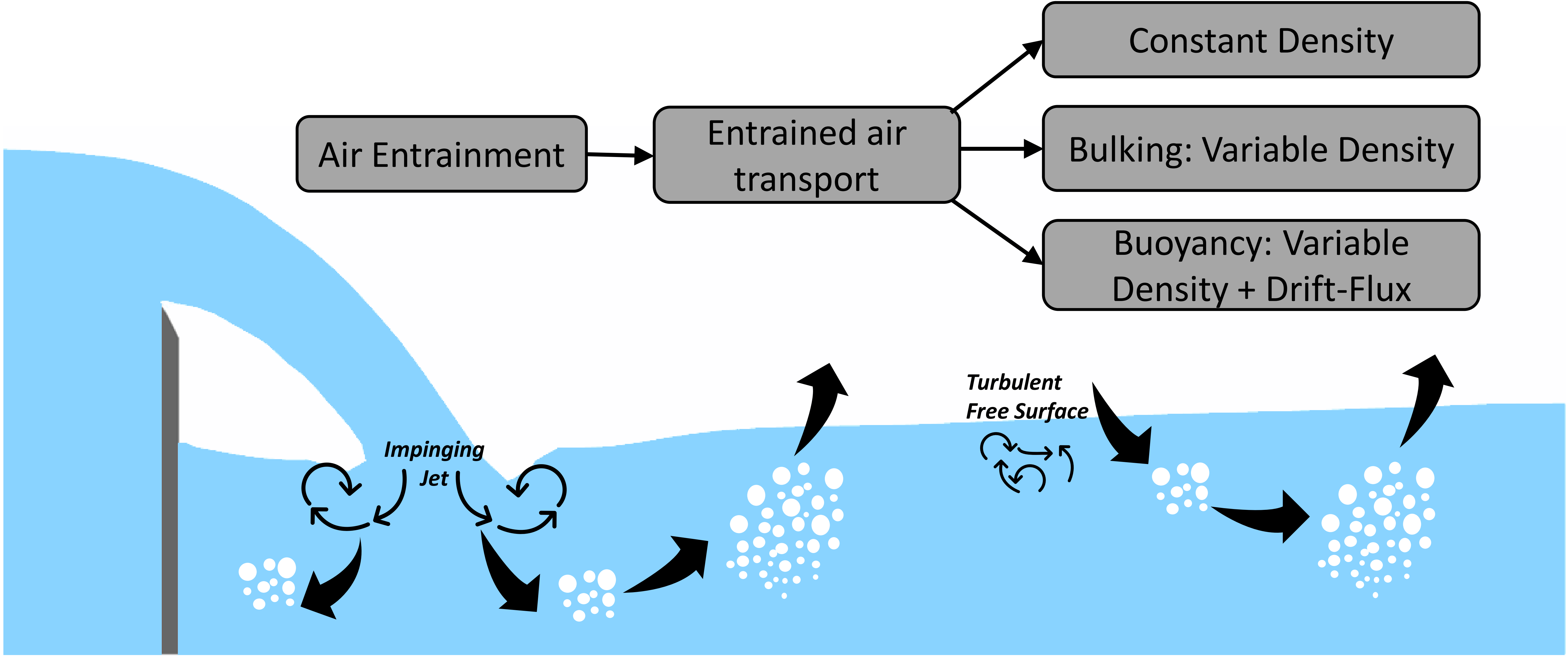
VOF methods: Drop Structure



2-fluid VOF model of a tangential dropshaft

Air entrainment

Air entrainment

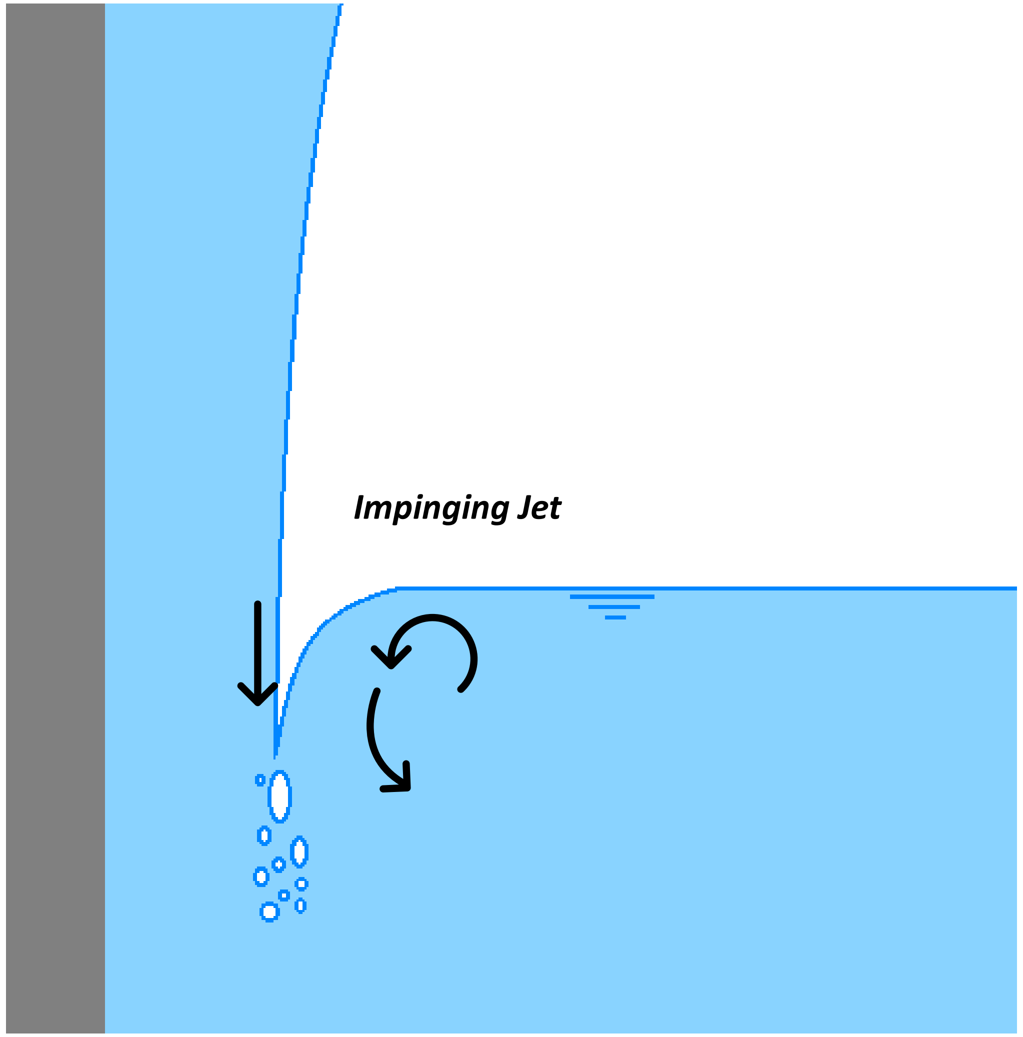

Air Entrainment → Entrained air transport

Entrained air transport → Constant Density

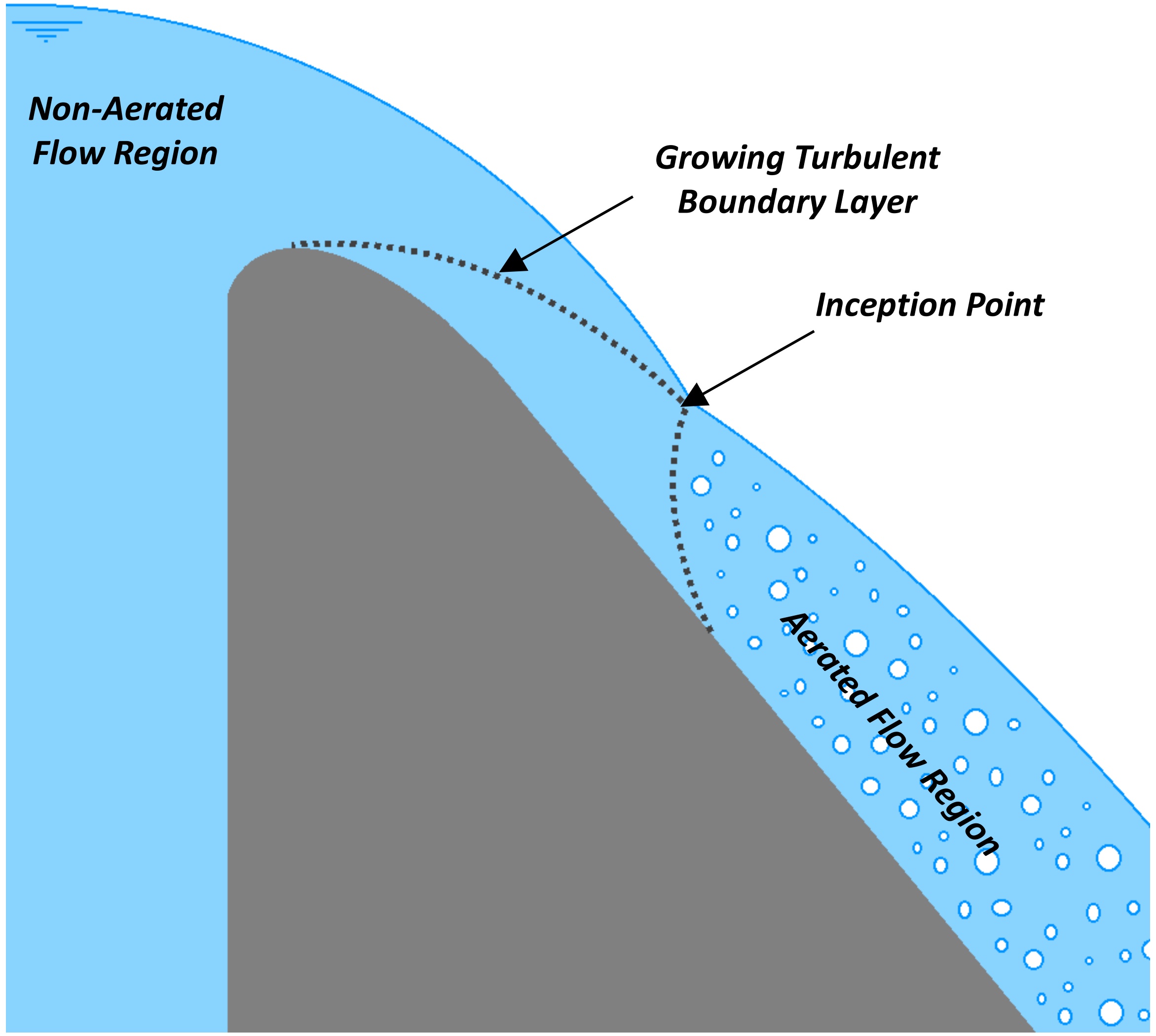
Entrained air transport → Bulking: Variable Density

Entrained air transport → Buoyancy: Variable Density + Drift-Flux

Air entrainment

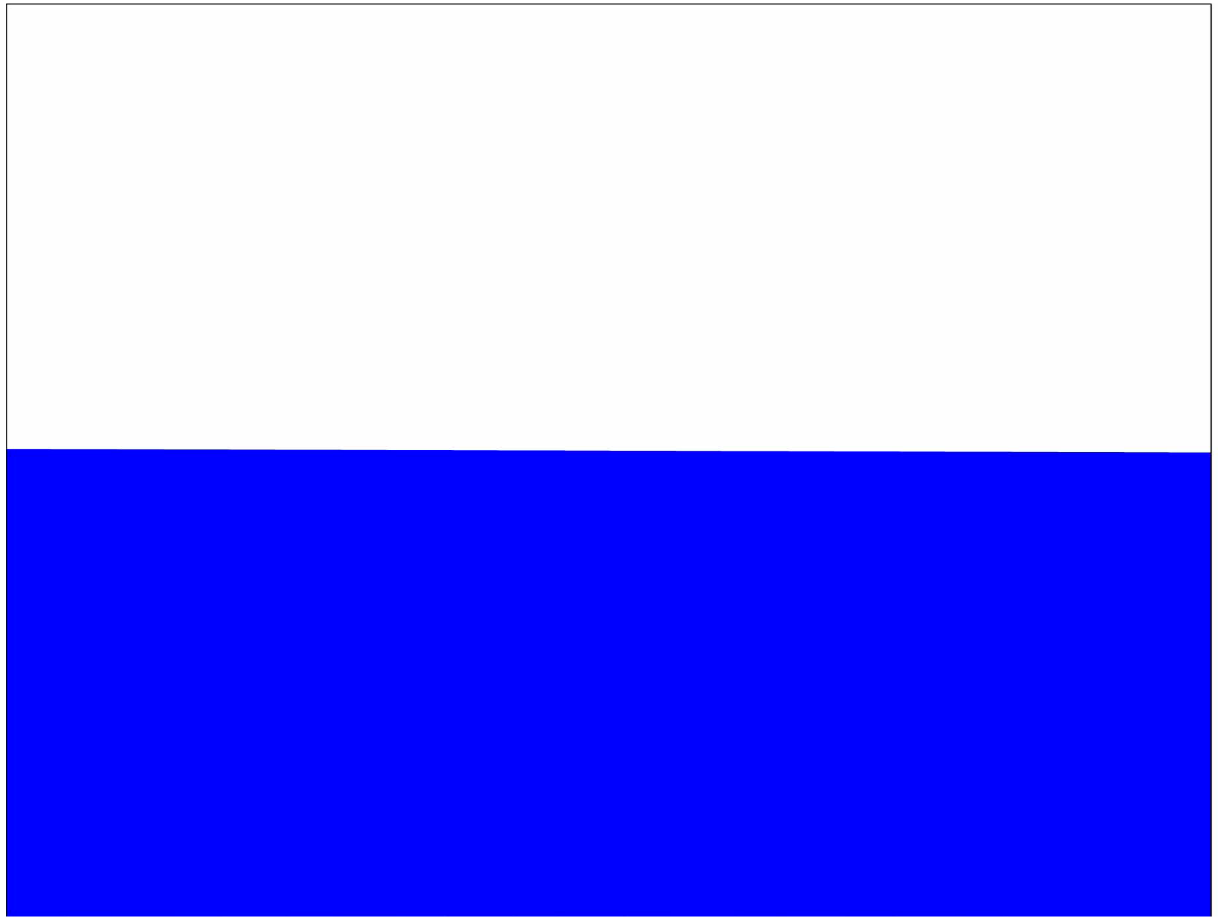


Localized Entrainment

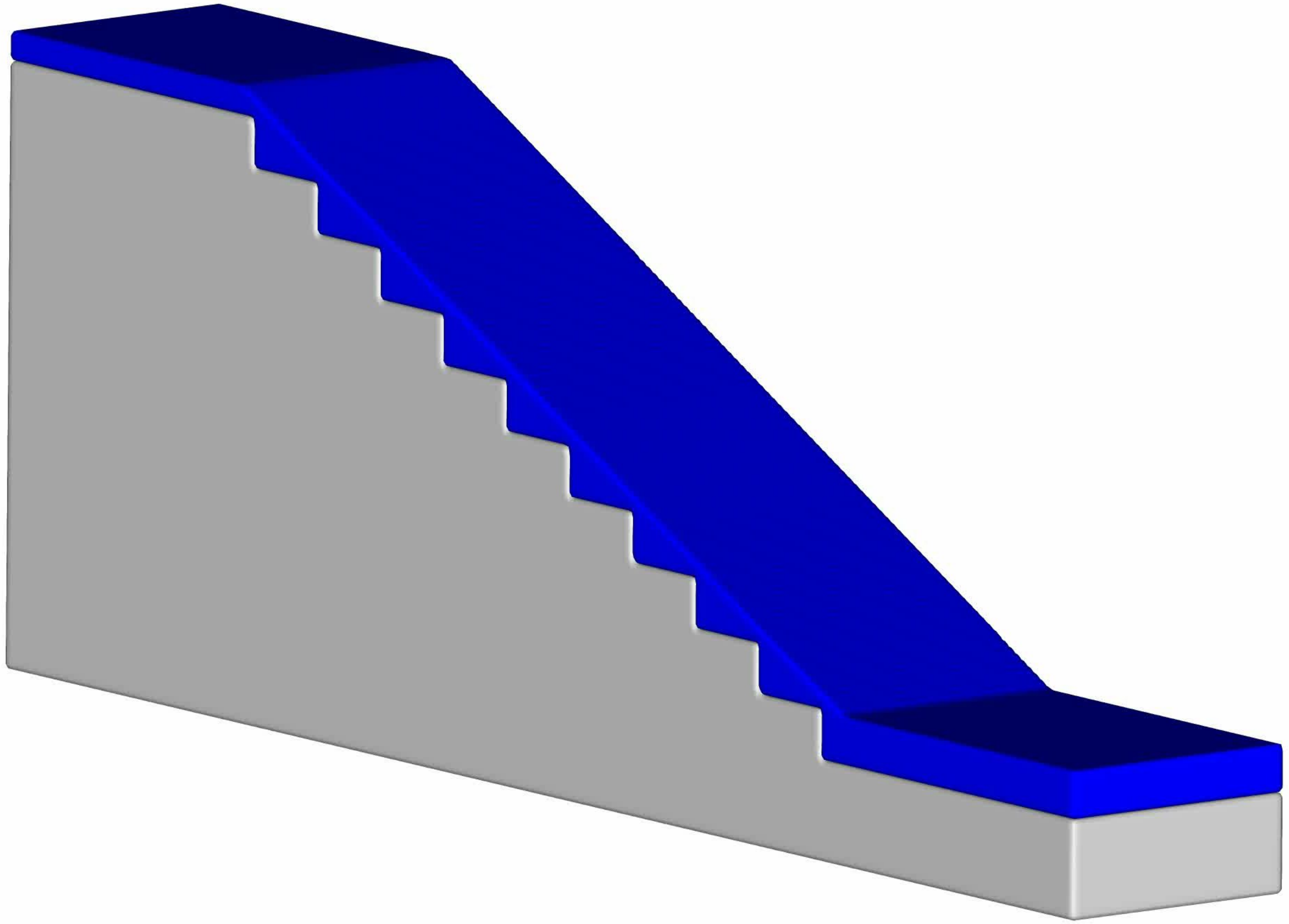


Turbulent Free Surface Entrainment

Air entrainment



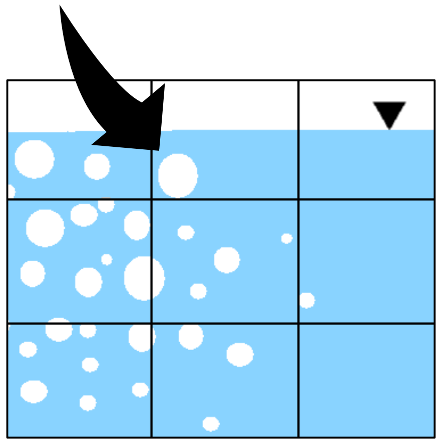
Localized Entrainment



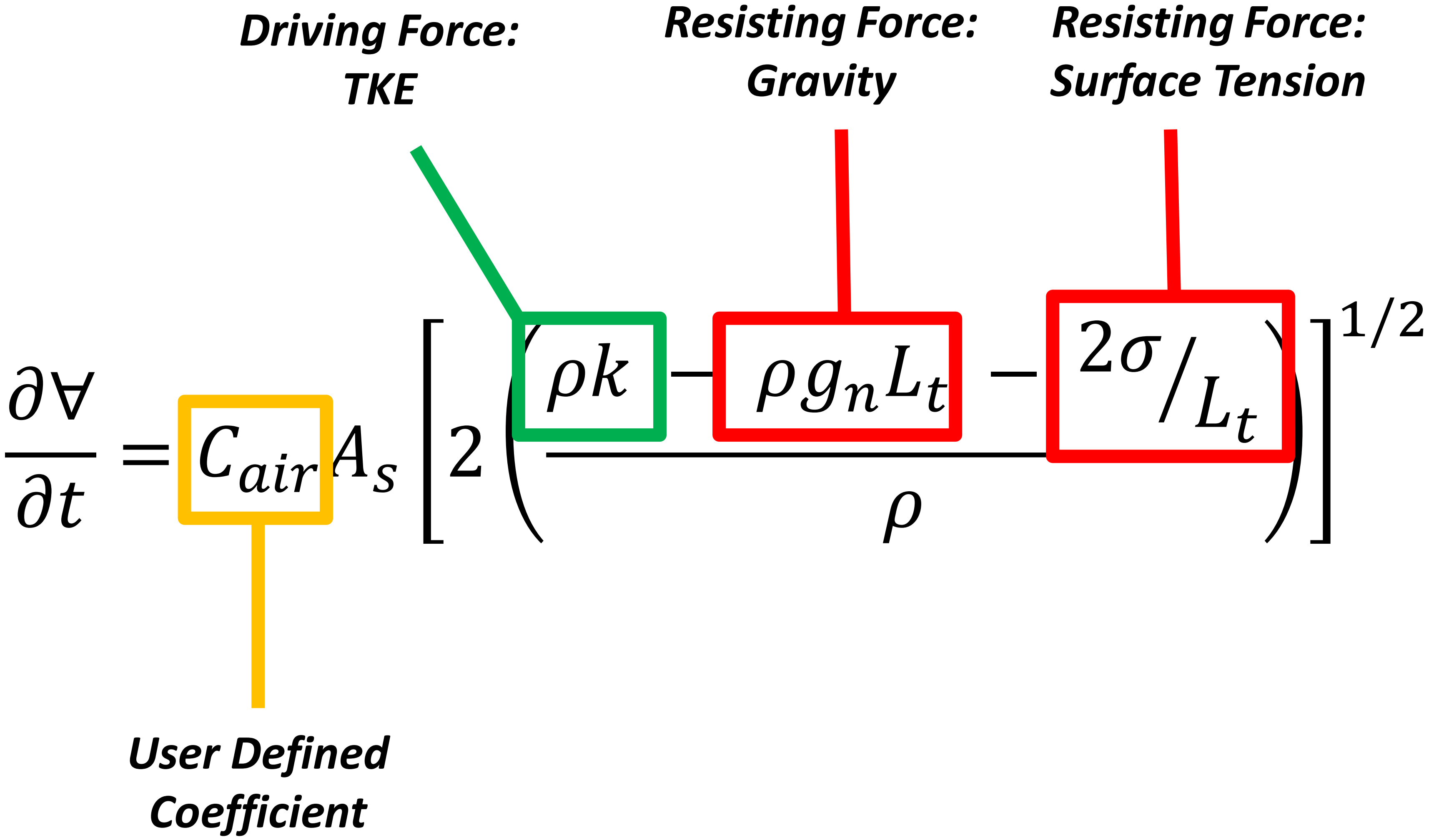
Turbulent Free Surface Entrainment

Air entrainment model

$Rate\ of\ entrained\ air = \frac{\partial \forall}{\partial t}$



$\forall$, Volume of air
C_{air}, Entrainment rate coefficient
A_s, Surface area of fluid
ρ, Fluid density
k, Turbulent kinetic energy
g_n, Gravity normal to surface
L_t, Turbulent length scale
σ, Surface tension coefficient



Driving Force: TKE

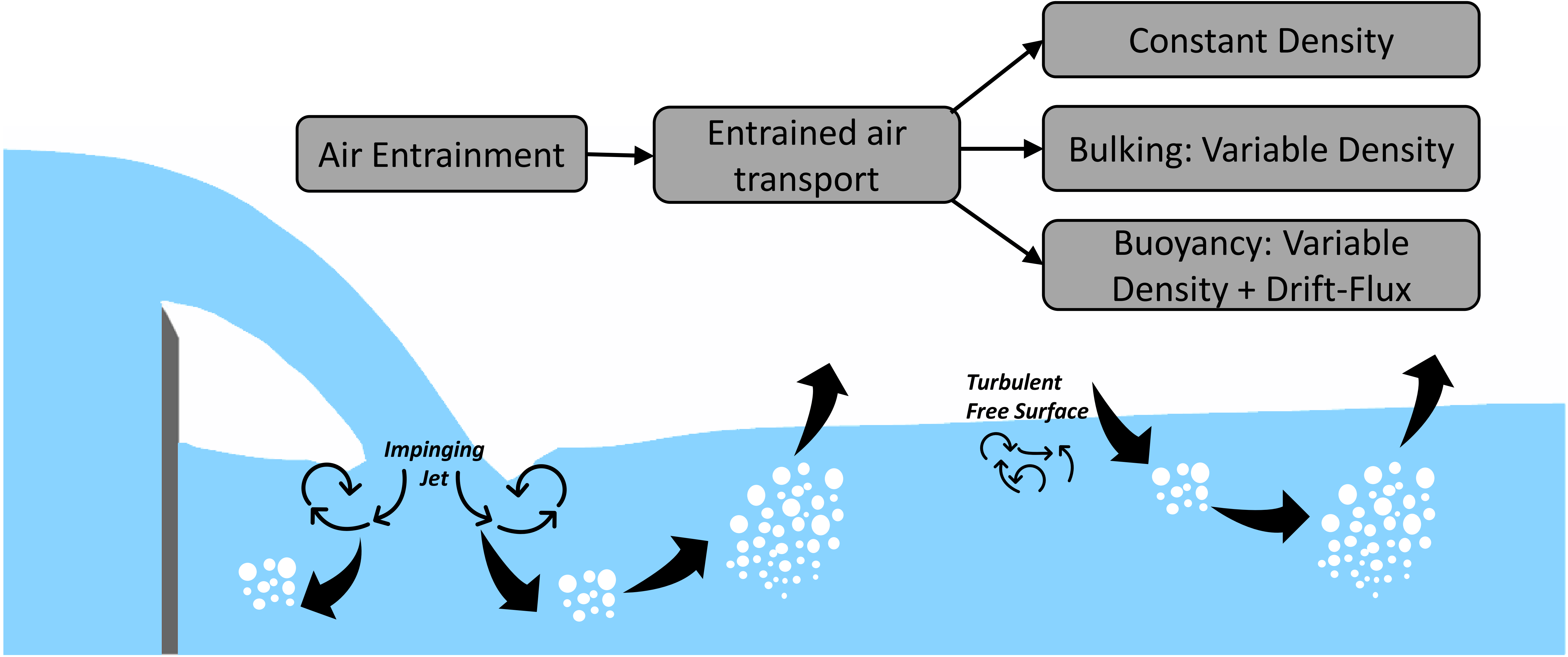
Resisting Force: Gravity

Resisting Force: Surface Tension

$$\frac{\partial \forall}{\partial t} = \boxed{C_{air}} A_s \left[2\left(\frac{\boxed{\rho k} - \boxed{\rho g_n L_t} - \boxed{{2\sigma}/{L_t}}}{\rho} \right) \right]^{1/2}$$

User Defined Coefficient

Air entrainment



Air Entrainment

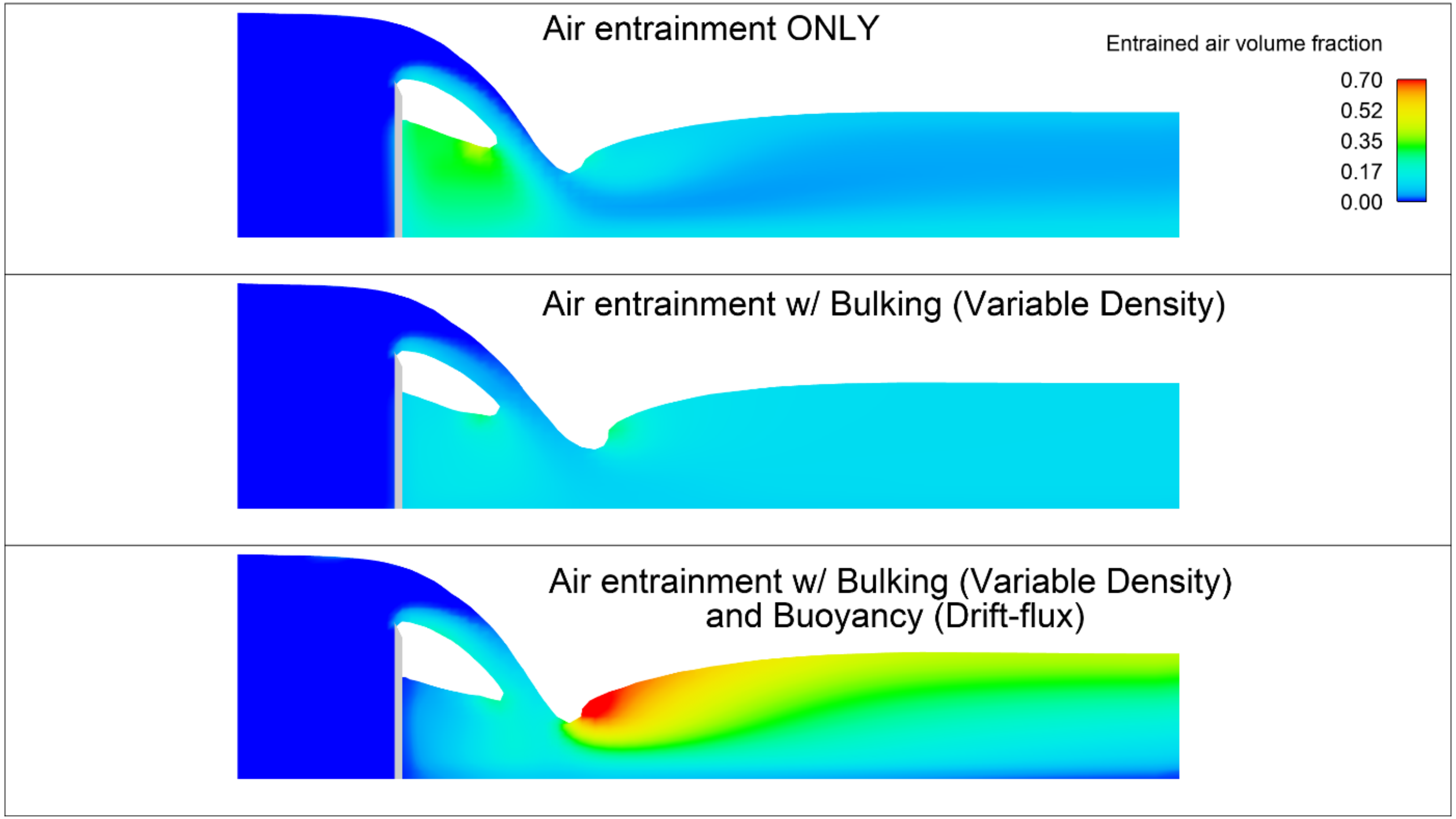
Entrained air transport

Constant Density

Bulking: Variable Density

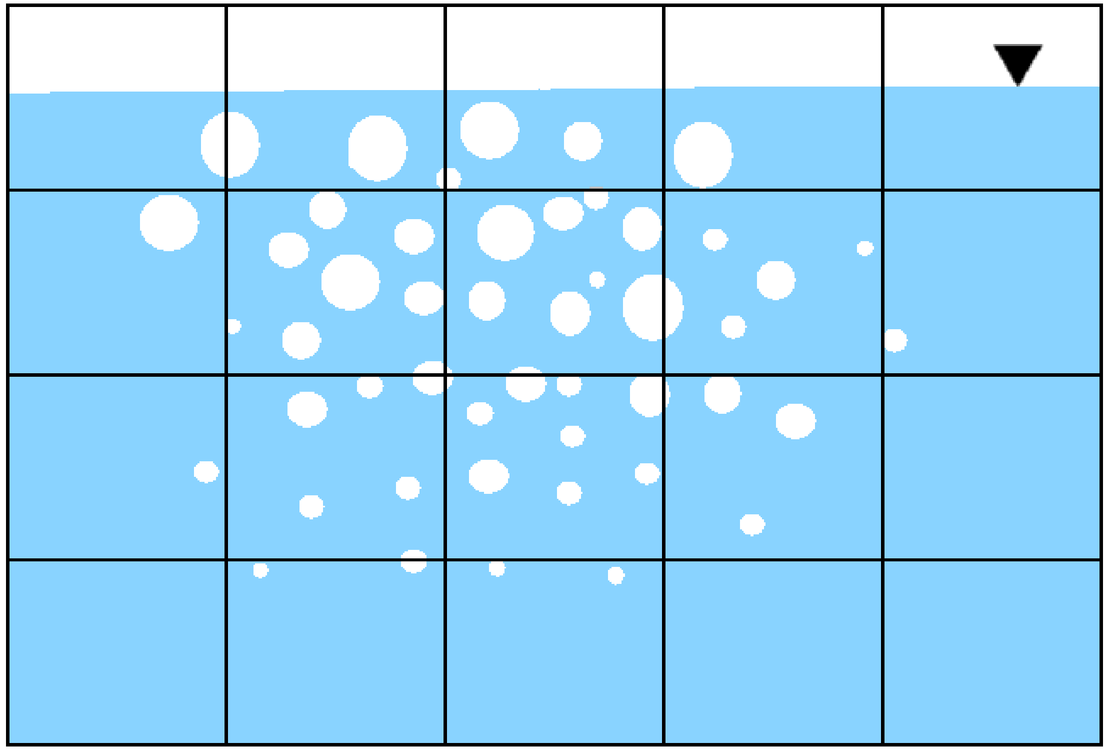
Buoyancy: Variable Density + Drift-Flux

Air entrainment

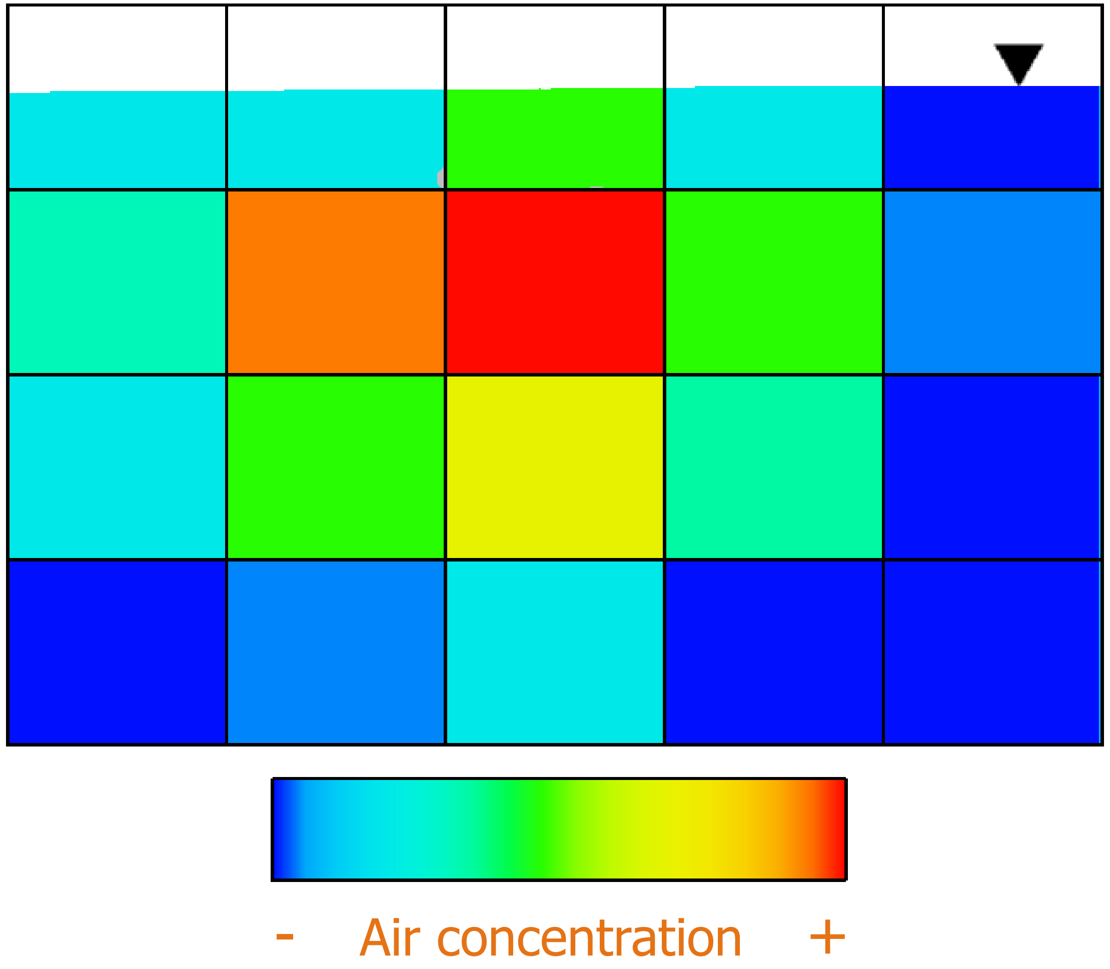


Air entrainment – scalar treatment

Physical representation

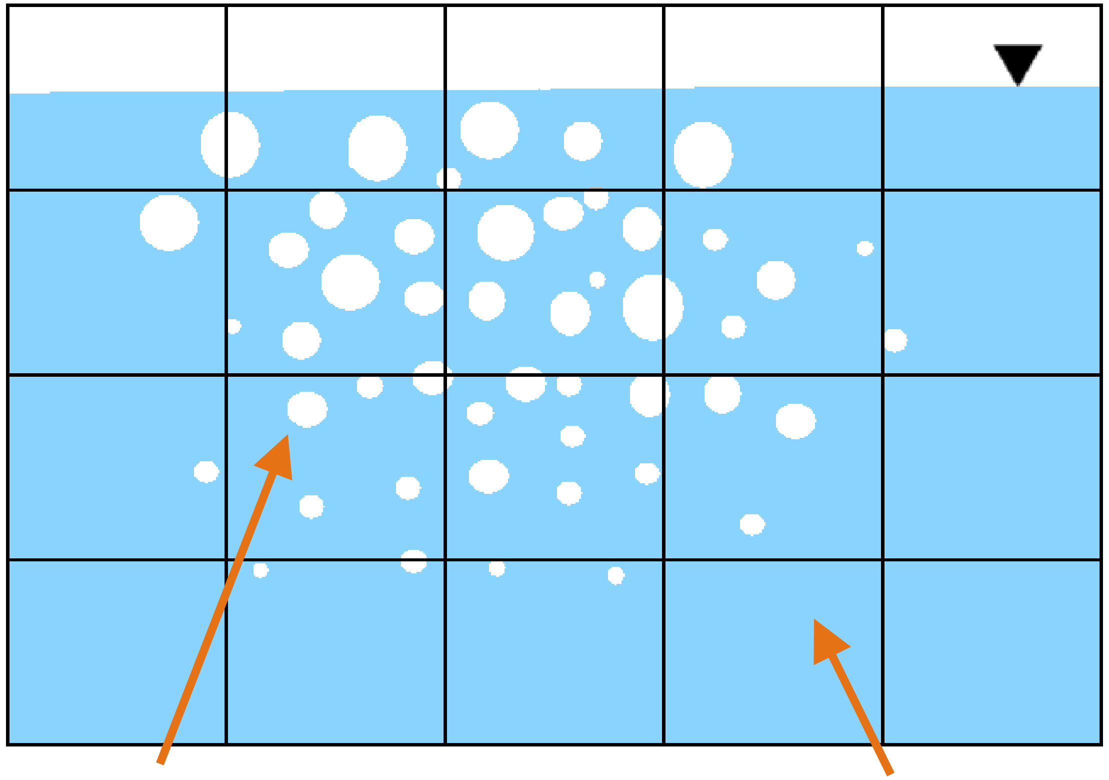


FLOW-3D numerical representation



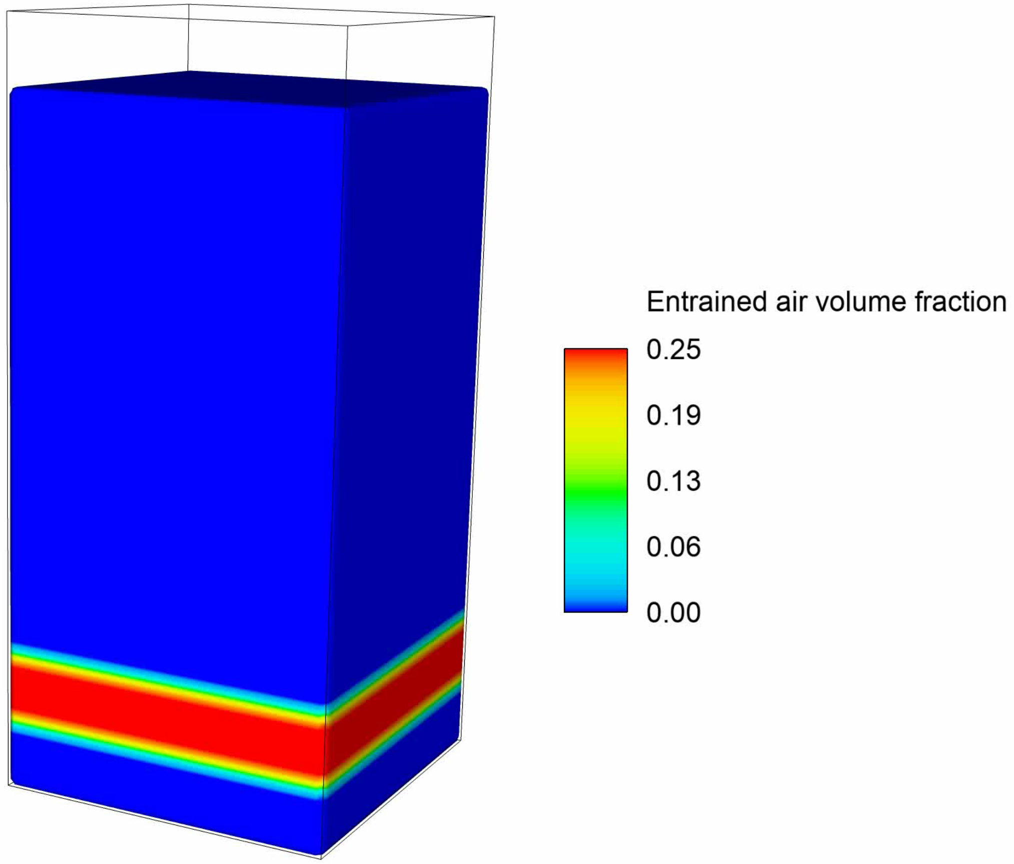
Air entrainment with drift-flux

Two-phase flow: liquid and gas

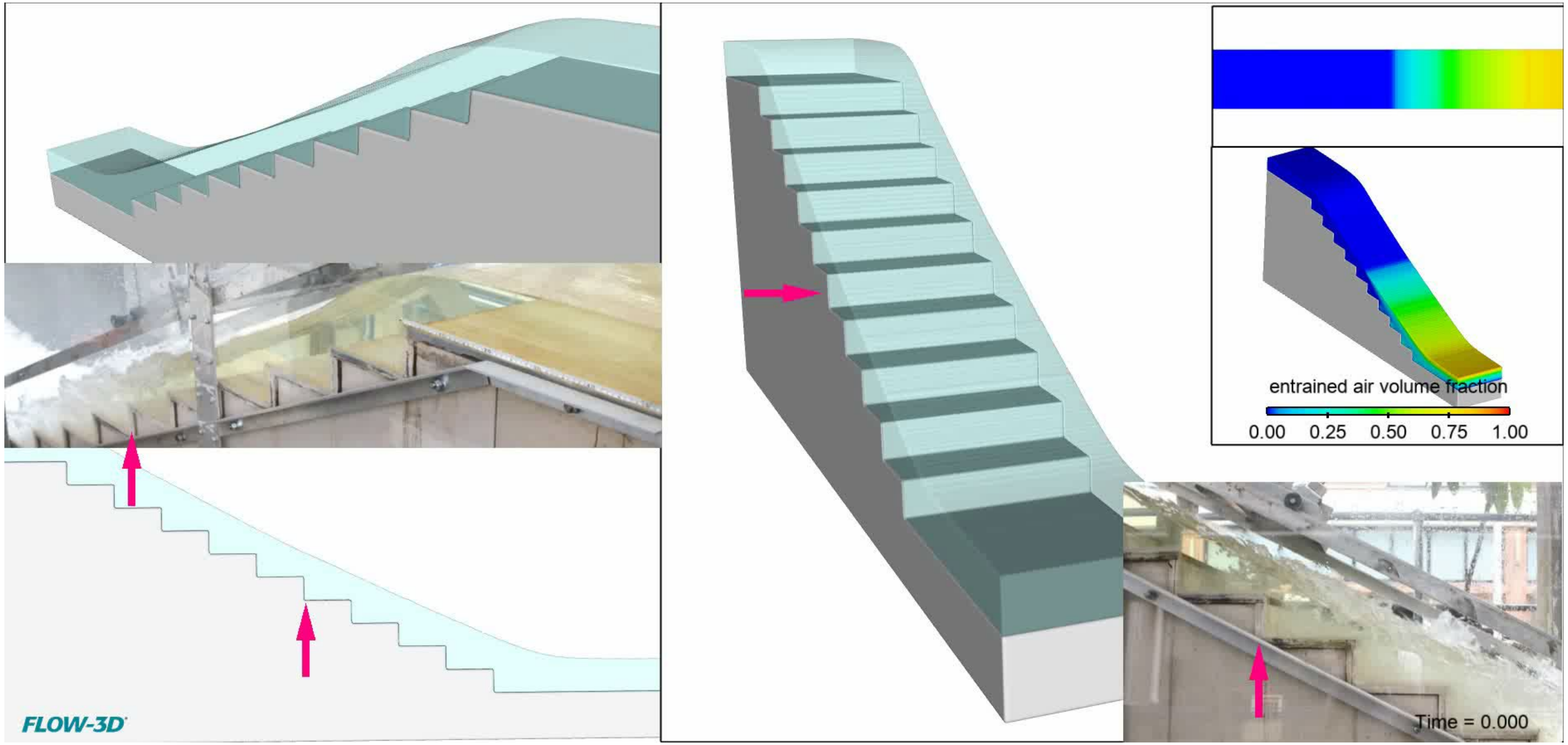


Air bubbles: gas phase

Water: liquid phase



Air entrainment – validations

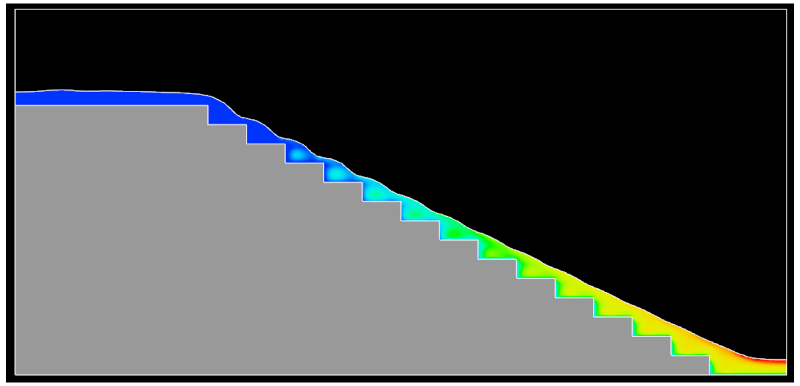


Air entrainment – validations

Q = 0.056 m3/s

Inception of air:

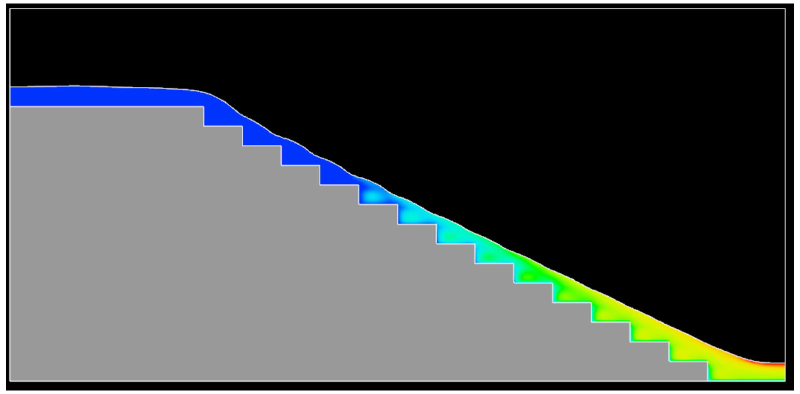
- Felder 2013: step 3-4
- *FLOW-3D*: step 3-4



Q = 0.095 m3/s

Inception of air:

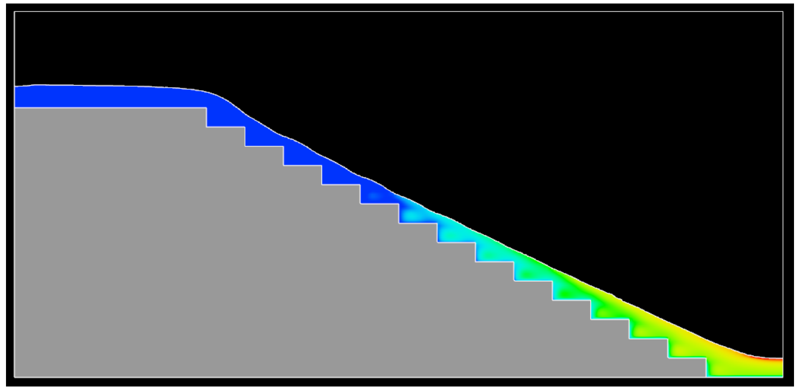
- Felder 2013: step 5
- *FLOW-3D*: step 5



Q = 0.116 m3/s

Inception of air:

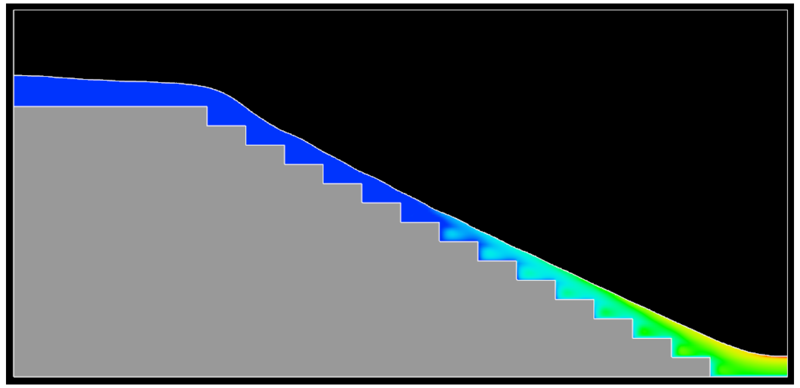
- Felder 2013: step 6
- *FLOW-3D*: step 6-7



Q = 0.161 m3/s

Inception of air:

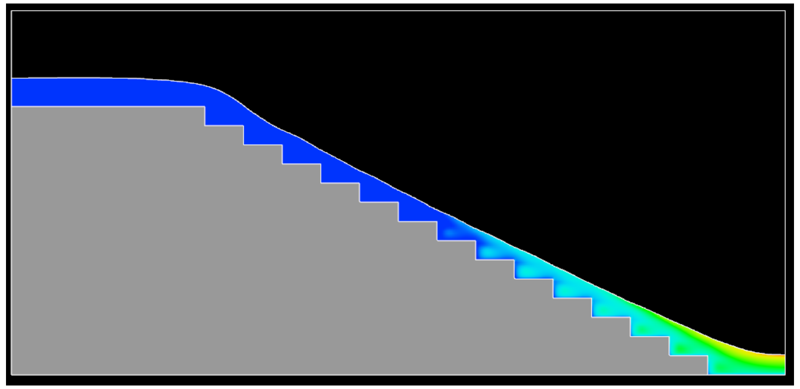
- Felder 2013: step 7-8
- *FLOW-3D*: step 7-8



Q = 0.180 m3/s

Inception of air:

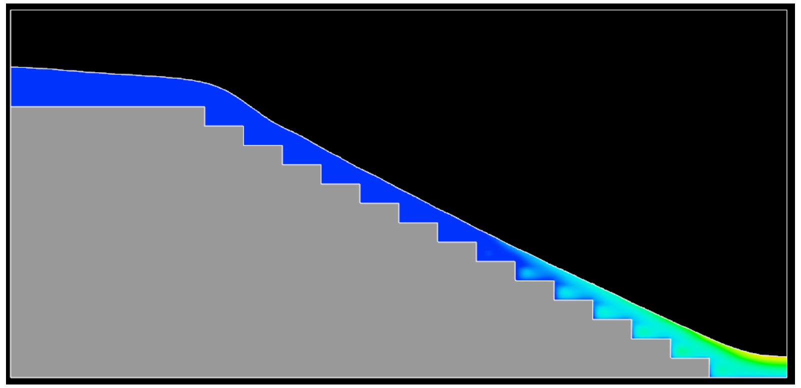
- Felder 2013: step 8
- *FLOW-3D*: step 8



Q = 0.227 m3/s

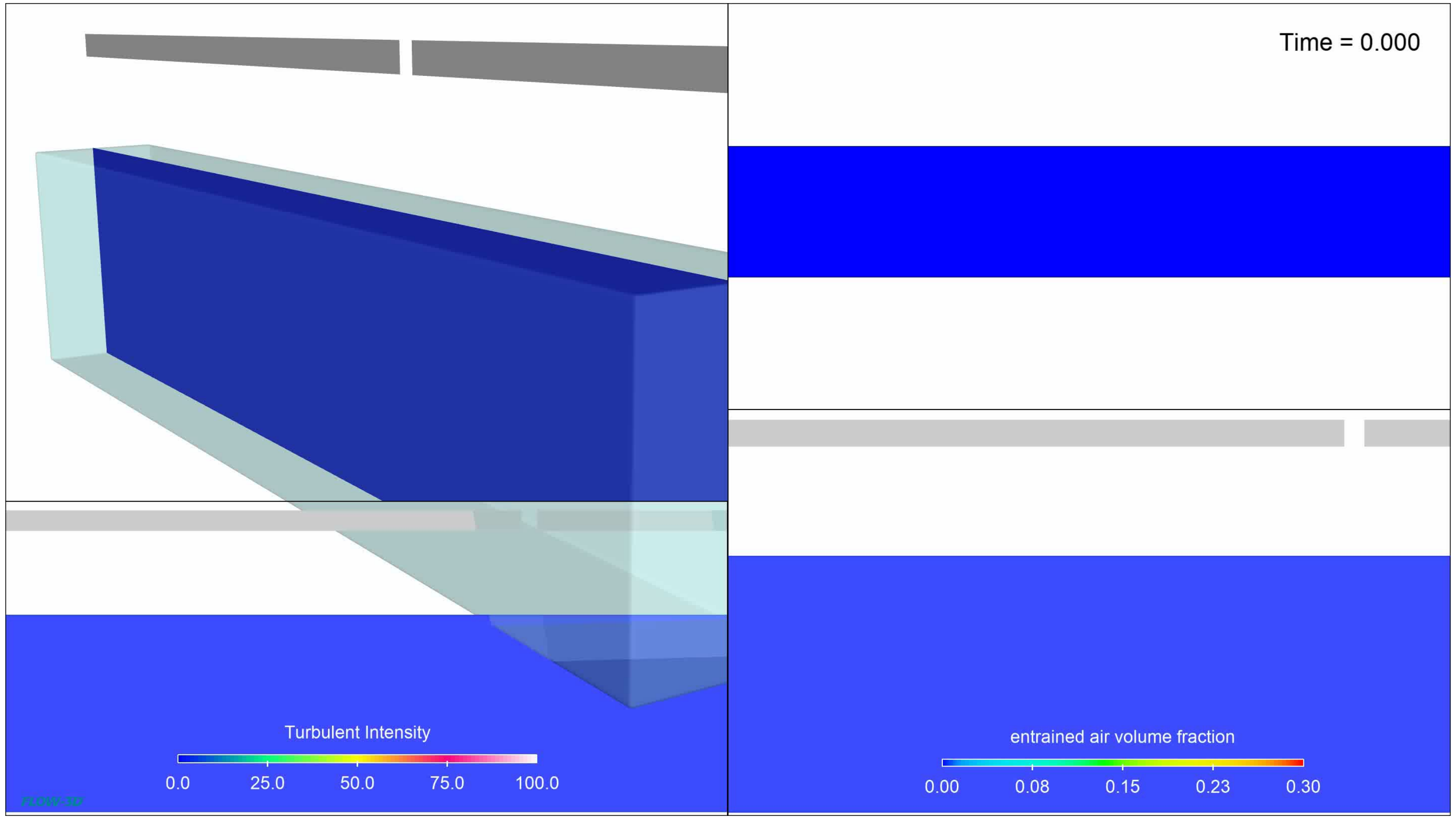
Inception of air:

- Felder 2013: step 10
- *FLOW-3D*: step 9-10



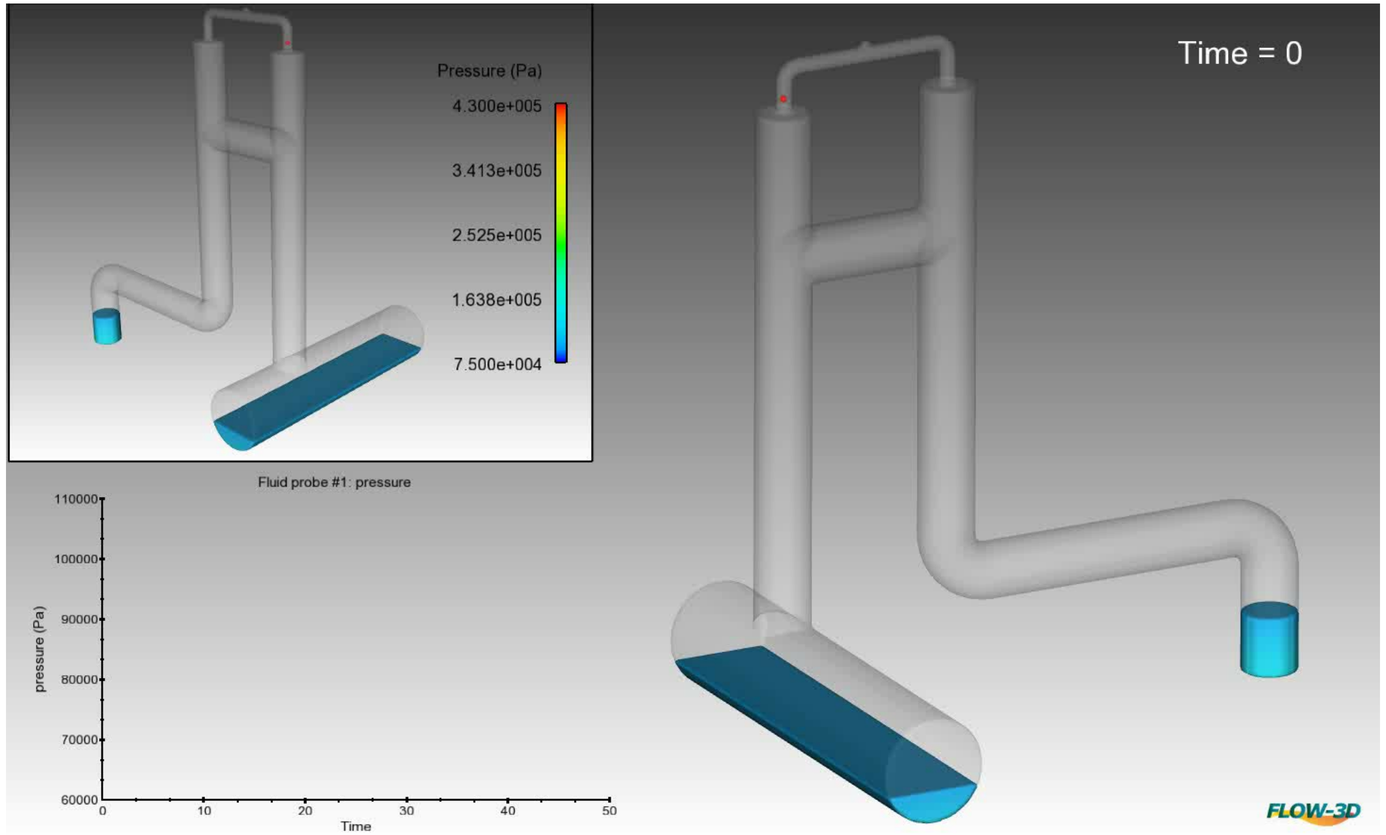
Air entrainment – plunging flow

- Plunging jet in cross stream
- Factor in:
  - Pre-existing entrained air in the flow / development of air entrainment within jet before impact
  - Bubble size distribution and evolution
  - Penetration depth

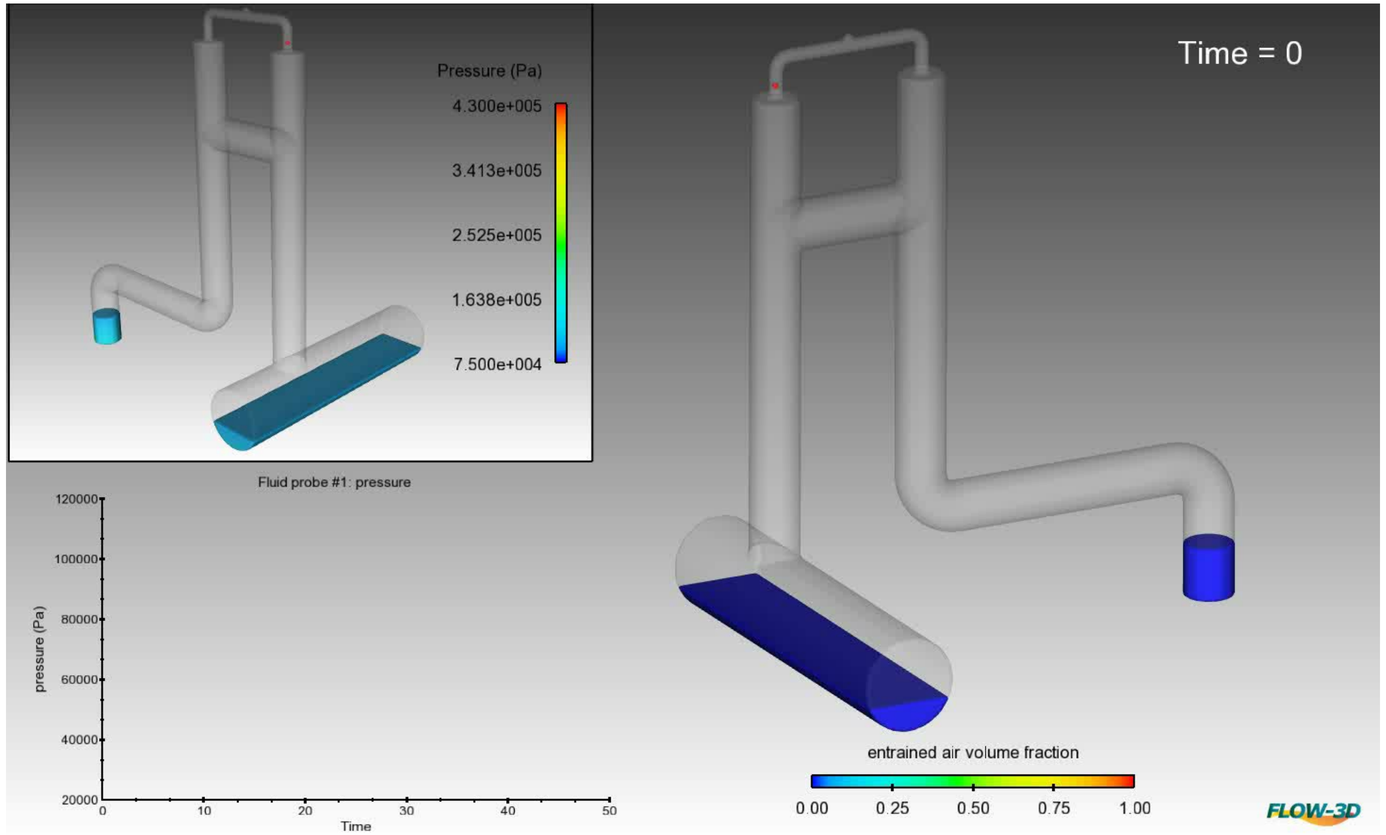


Air entrainment in Closed Conduits

Adiabatic bubble model: allows void regions to pressurize/depressurize



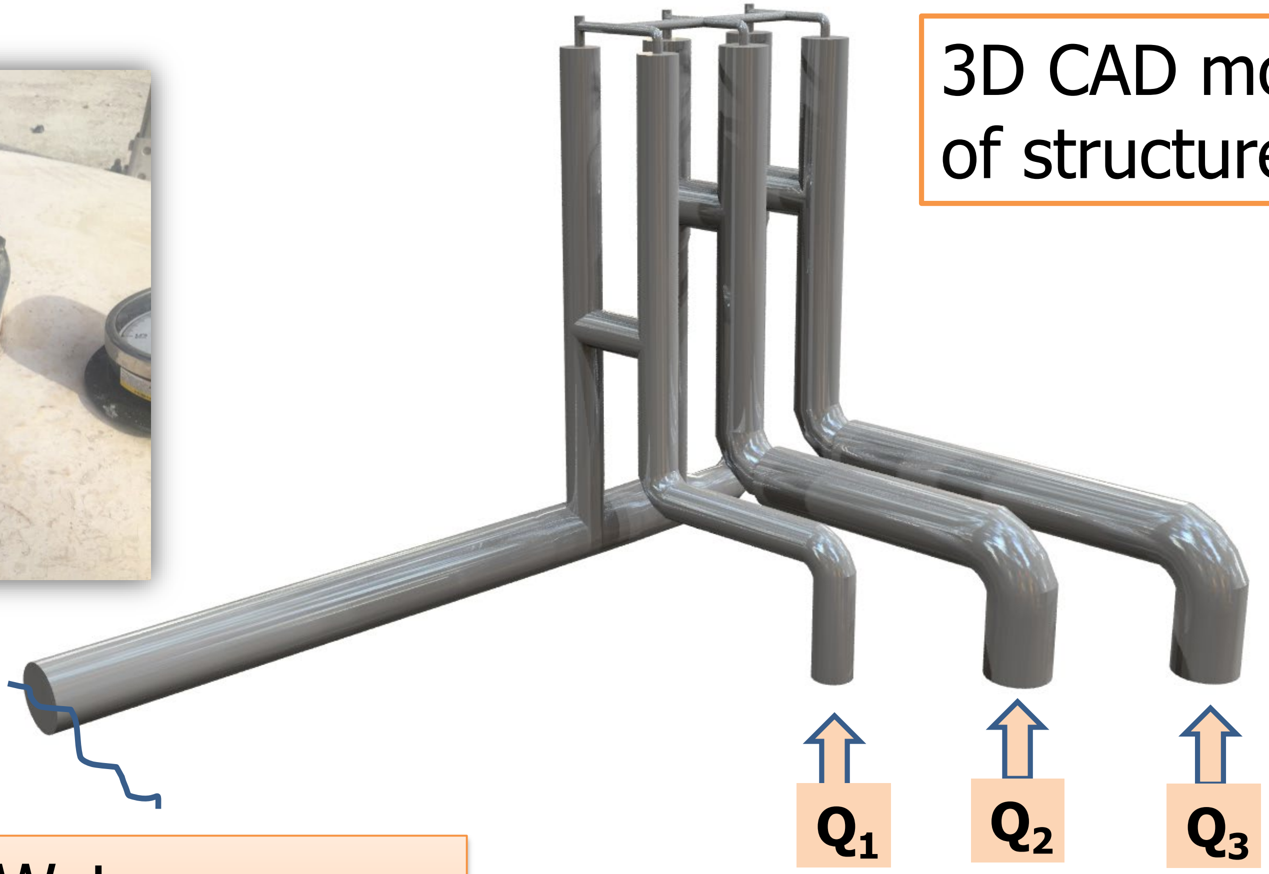
Without adiabatic model + air entrainment



With adiabatic model + air entrainment

Case Study: Air entrainment in Closed Conduits

- 12’-9” interceptor
- Pump station – two incidents when pump 1 was shut down

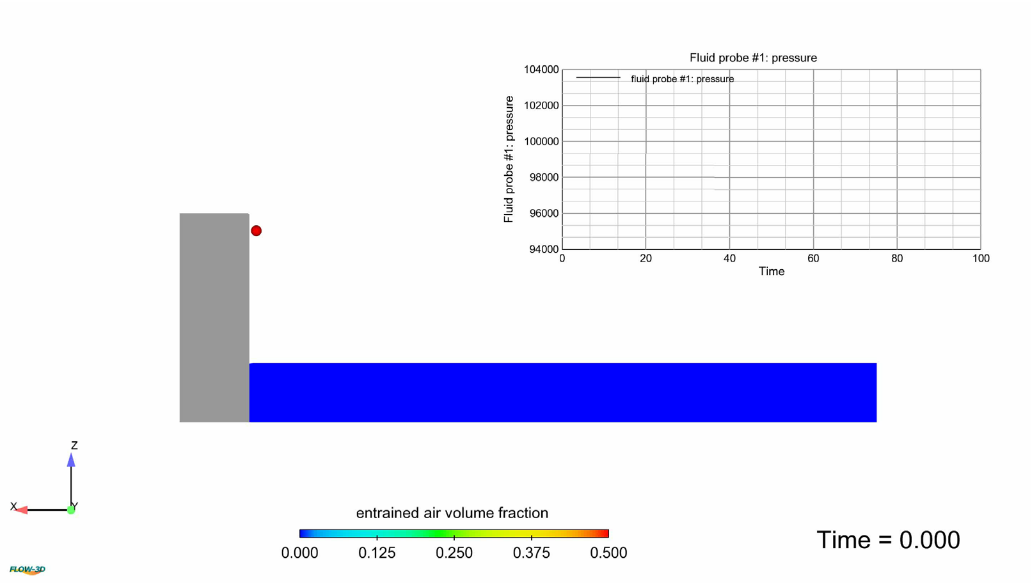


3D CAD model of structure

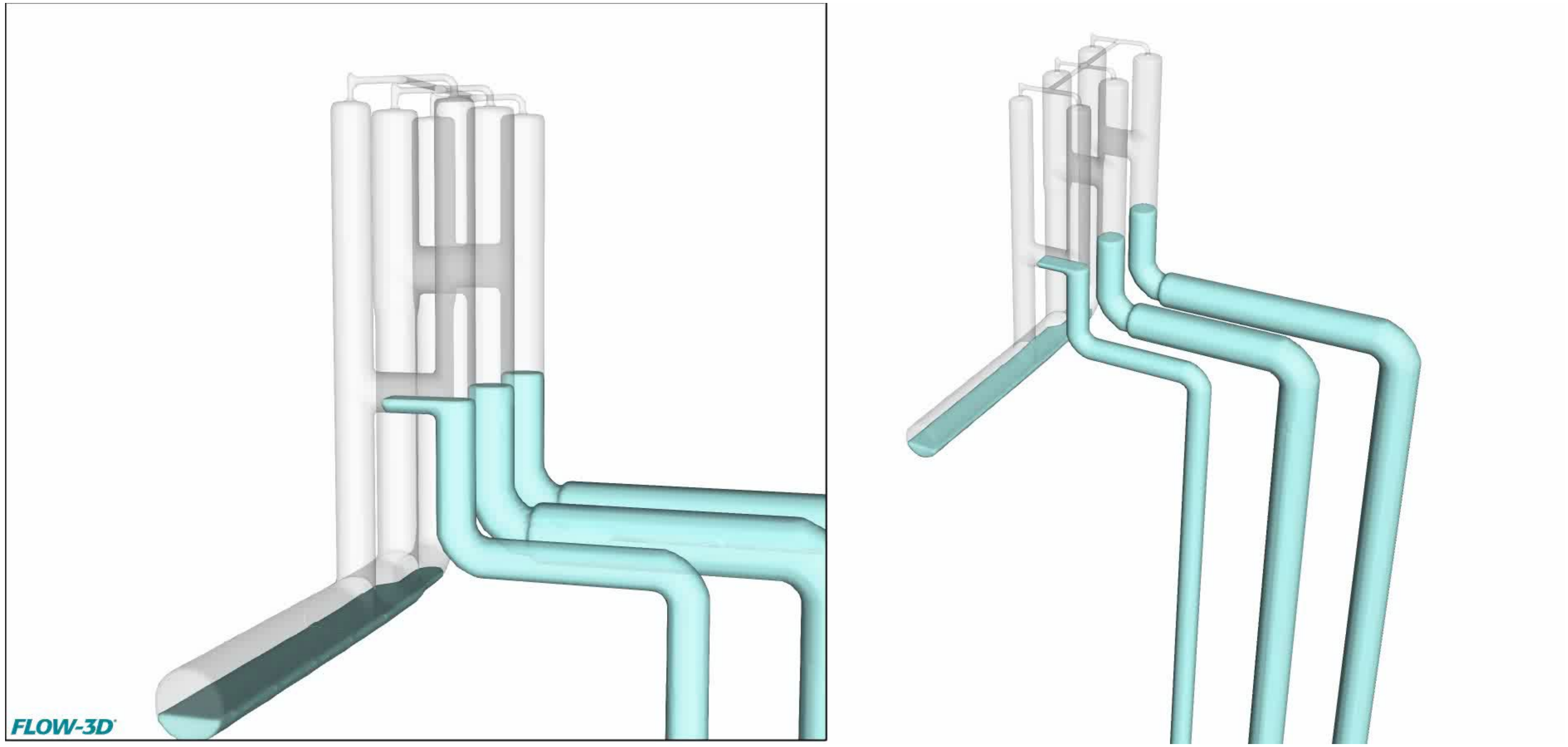
Water elevation at outlet

Michalski, J., and Wendelbo, J., “Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues”, WEFTEC 2018.

Case Study: Air entrainment in Closed Conduits



Simple weir flow case with adiabatic bubble model on

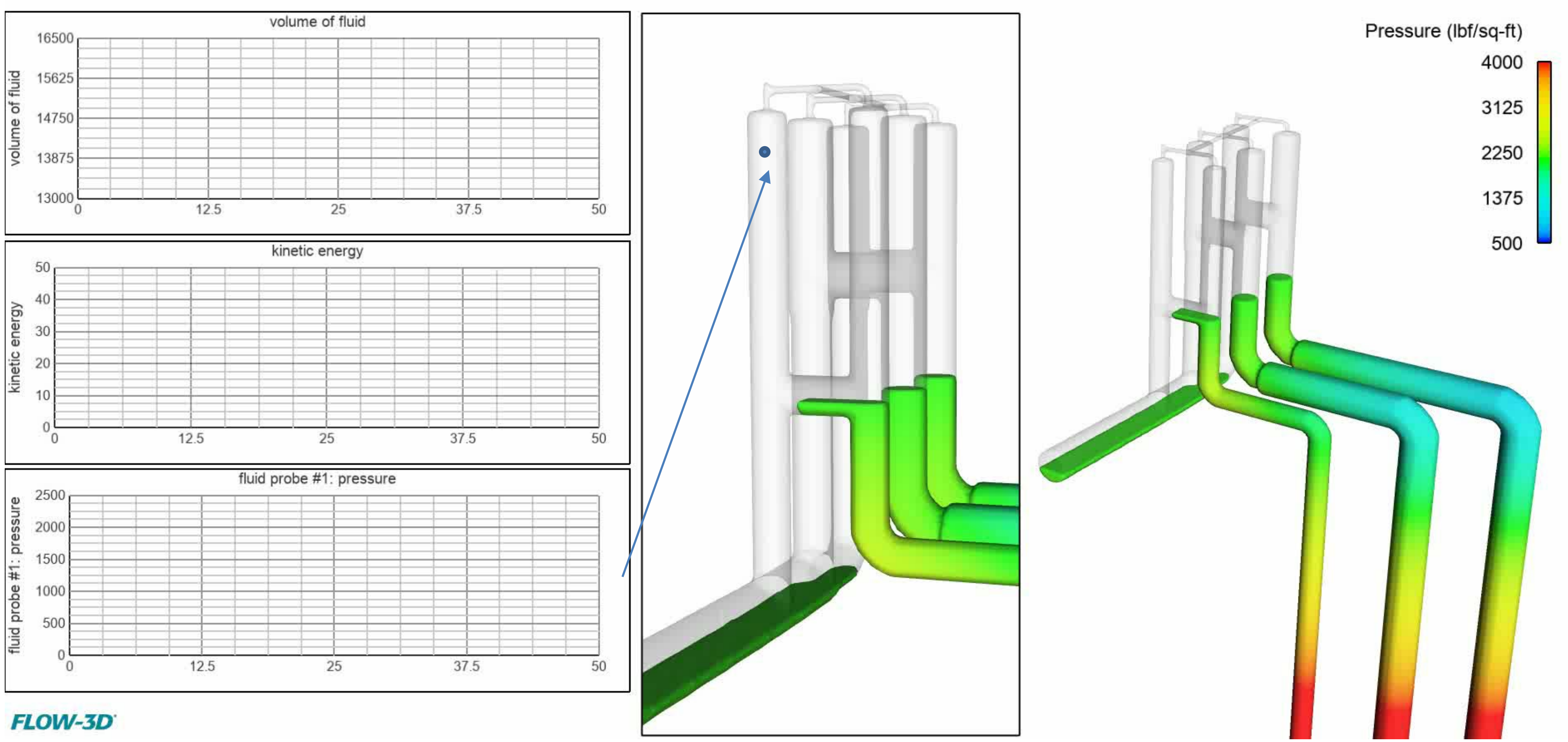


Normal operation with all three pumps running

Flow condition Q1 = 100cfs, Q2 = 150cfs, Q3 = 150cfs – vented flow

Michalski, J., and Wendelbo, J., “Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues”, WEFTEC 2018.

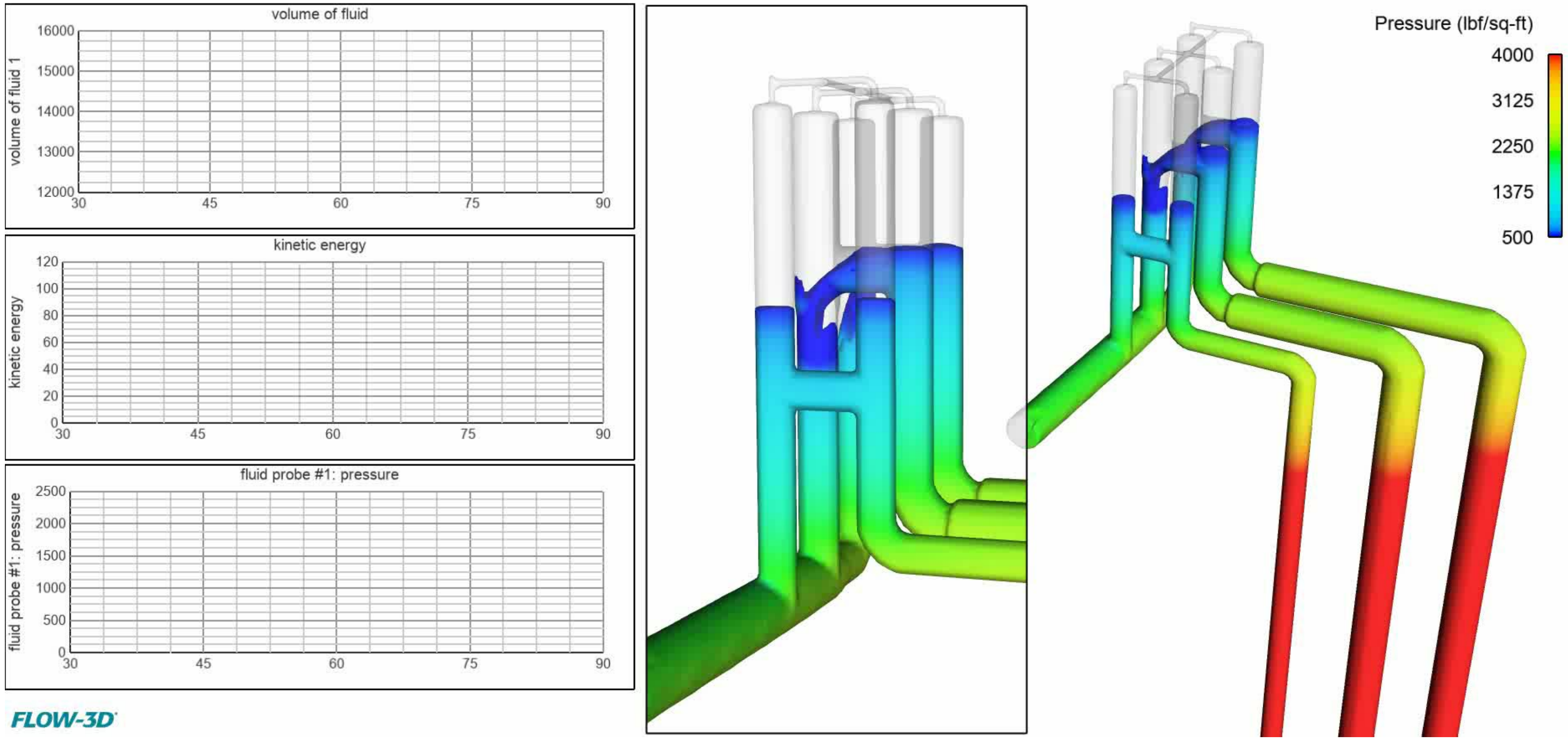
Case Study: Air entrainment in Closed Conduits



Flow condition Q1 = 100cfs, Q2 = 150cfs, Q3 = 150cfs – vented flow
Normal operation with all three pumps running – Tailwater elevation
determine by flow (no back pressure)

Michalski, J., and Wendelbo, J., “Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues”, WEFTEC 2018.

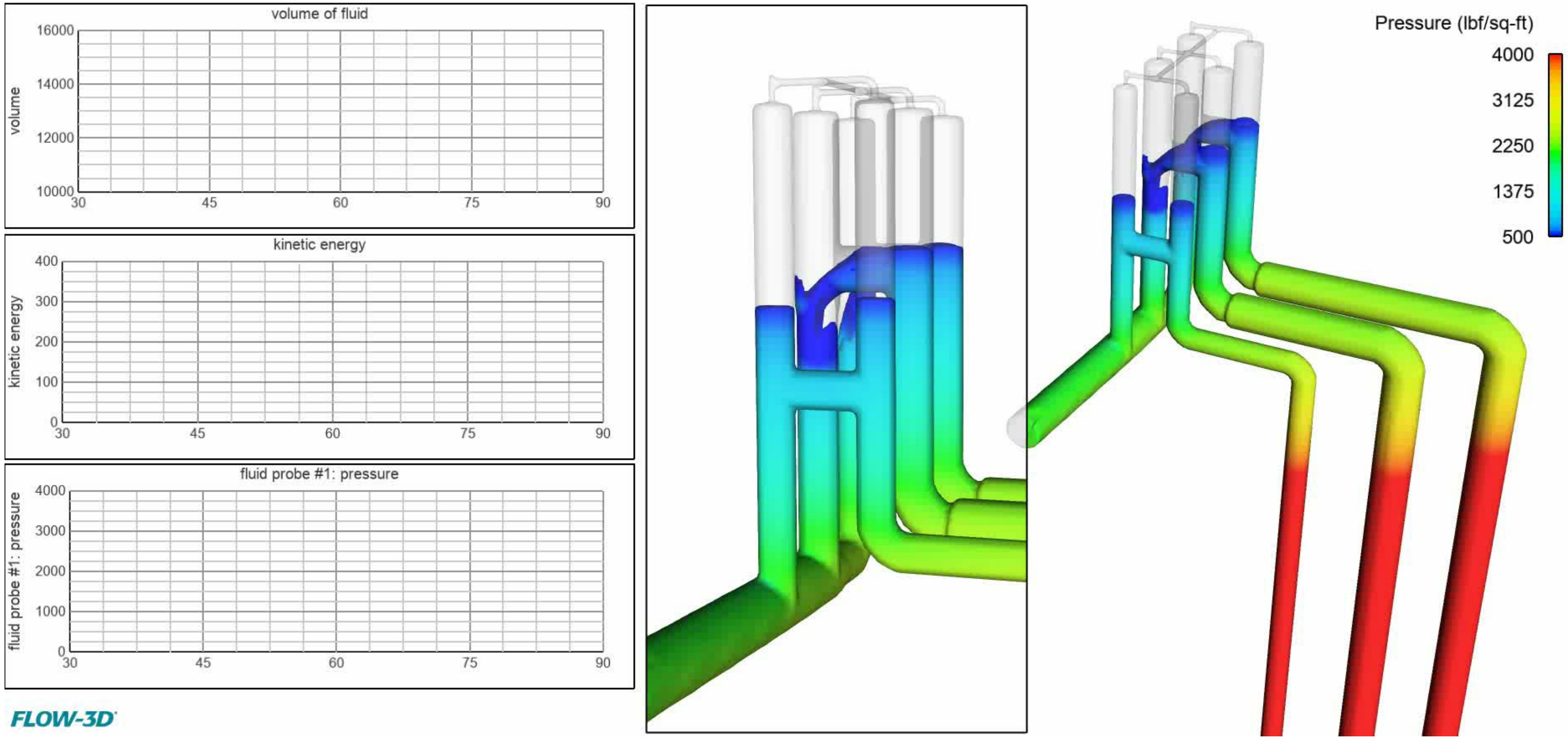
Case Study: Air entrainment in Closed Conduits



Flow condition Q1 = 0 cfs, Q2 = 150cfs, Q3 = 150cfs – vented flow
Normal operation with all three pumps running – Tailwater elevation determine by flow (no back pressure)

Michalski, J., and Wendelbo, J., "Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues", WEFTEC 2018.

Case Study: Air entrainment in Closed Conduits

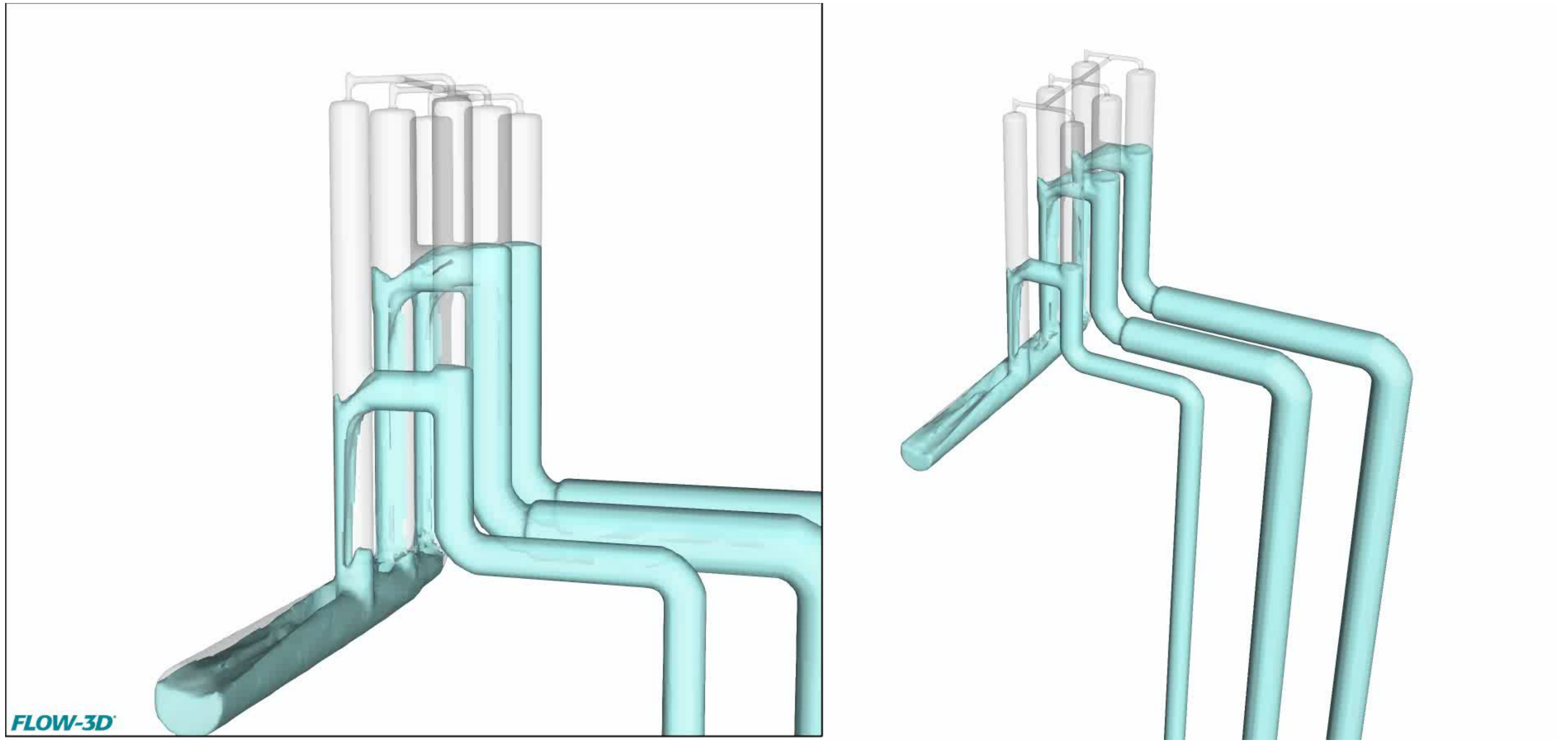


Flow condition Q1 = 150 cfs, Q2 = 150cfs, Q3 = 0 cfs – vented flow
Normal operation with all three pumps running – Tailwater elevation determine by flow (no back pressure)

Michalski, J., and Wendelbo, J., "Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues", WEFTEC 2018.

Case Study: Air entrainment in Closed Conduits

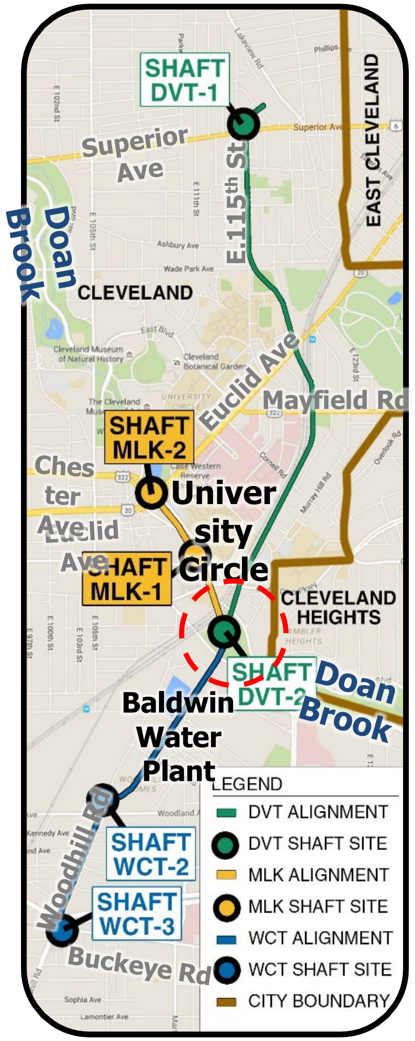
- Expected behaviors are reproduced
- Assumptions on modeled physics are sound
    - Siphon and air entrainment physical assumptions make sense (as is well known for self priming siphons)
- Demonstrates how CFD analysis can be used as a forensic tool

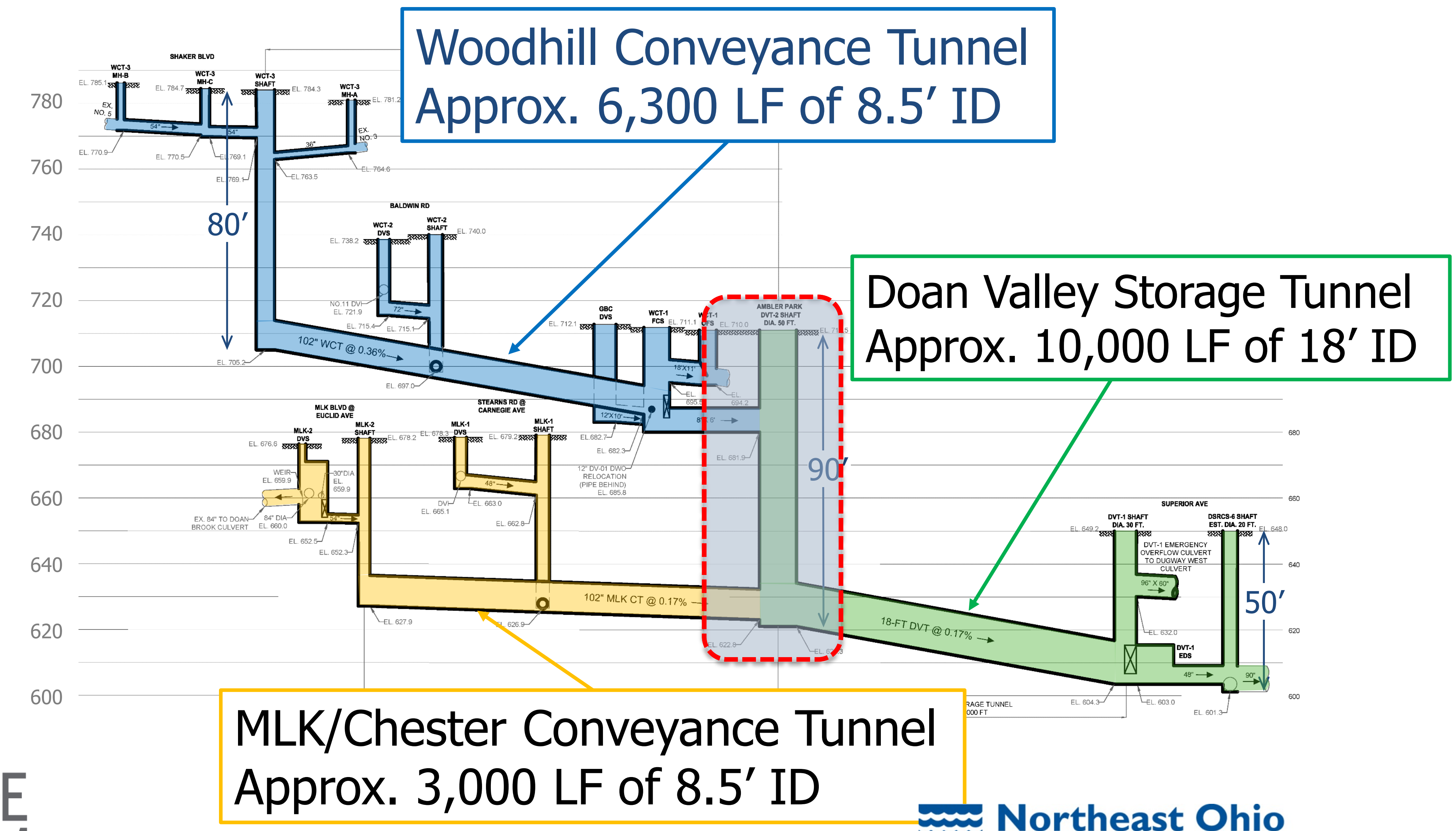


Pressure equalization: placement of two-way valves in the system

Michalski, J., and Wendelbo, J., “Utilizing CFD Methods as a Forensic Tool in Pipeline Systems to Assess Air/Water Transient Issues”, WEFTEC 2018.

Case Study: NEORSD Baffle Dropshaft





Woodhill Conveyance Tunnel
Approx. 6,300 LF of 8.5’ ID

Doan Valley Storage Tunnel
Approx. 10,000 LF of 18’ ID

MLK/Chester Conveyance Tunnel
Approx. 3,000 LF of 8.5’ ID

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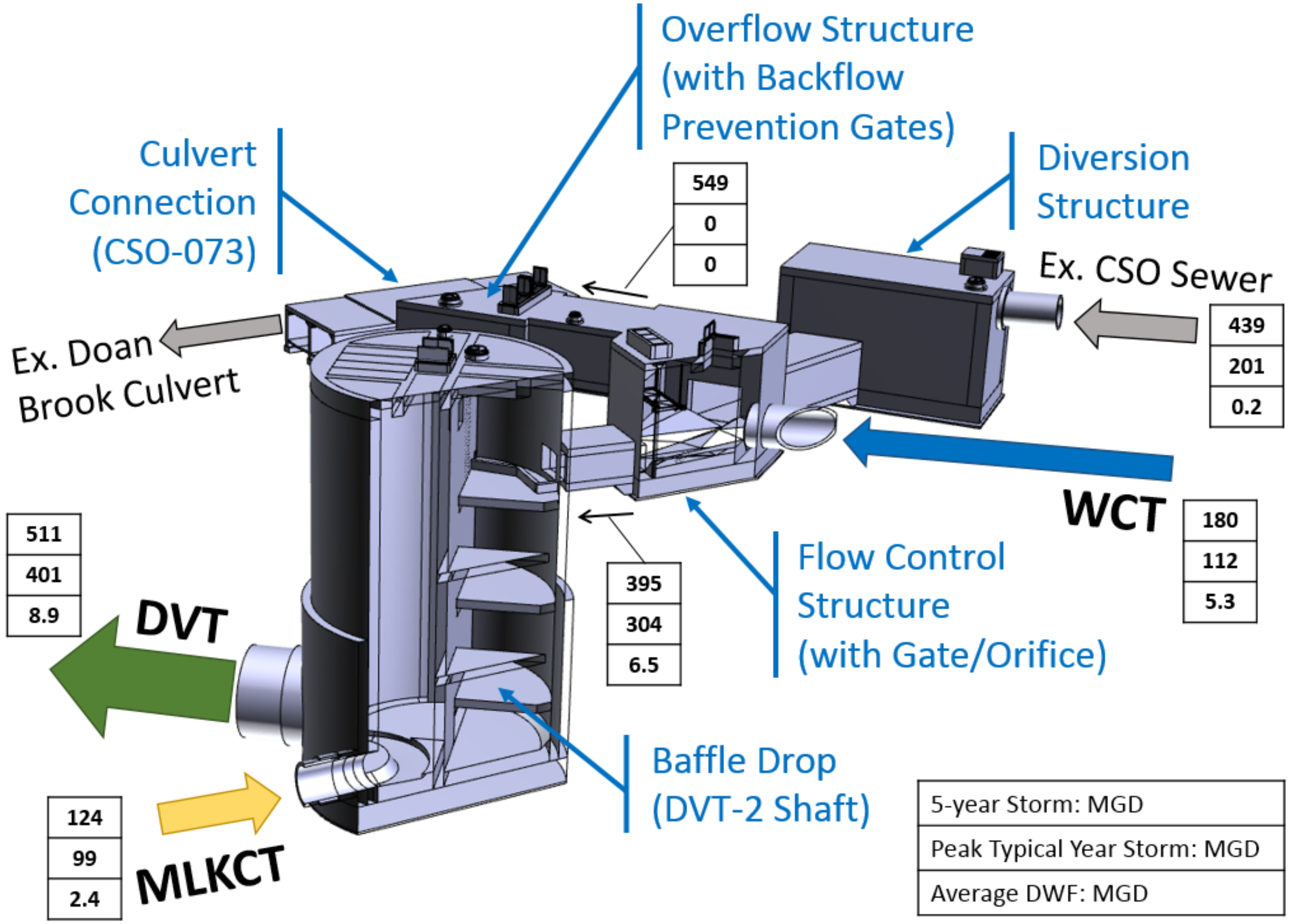
WADE TRIM

Northeast Ohio Regional Sewer District

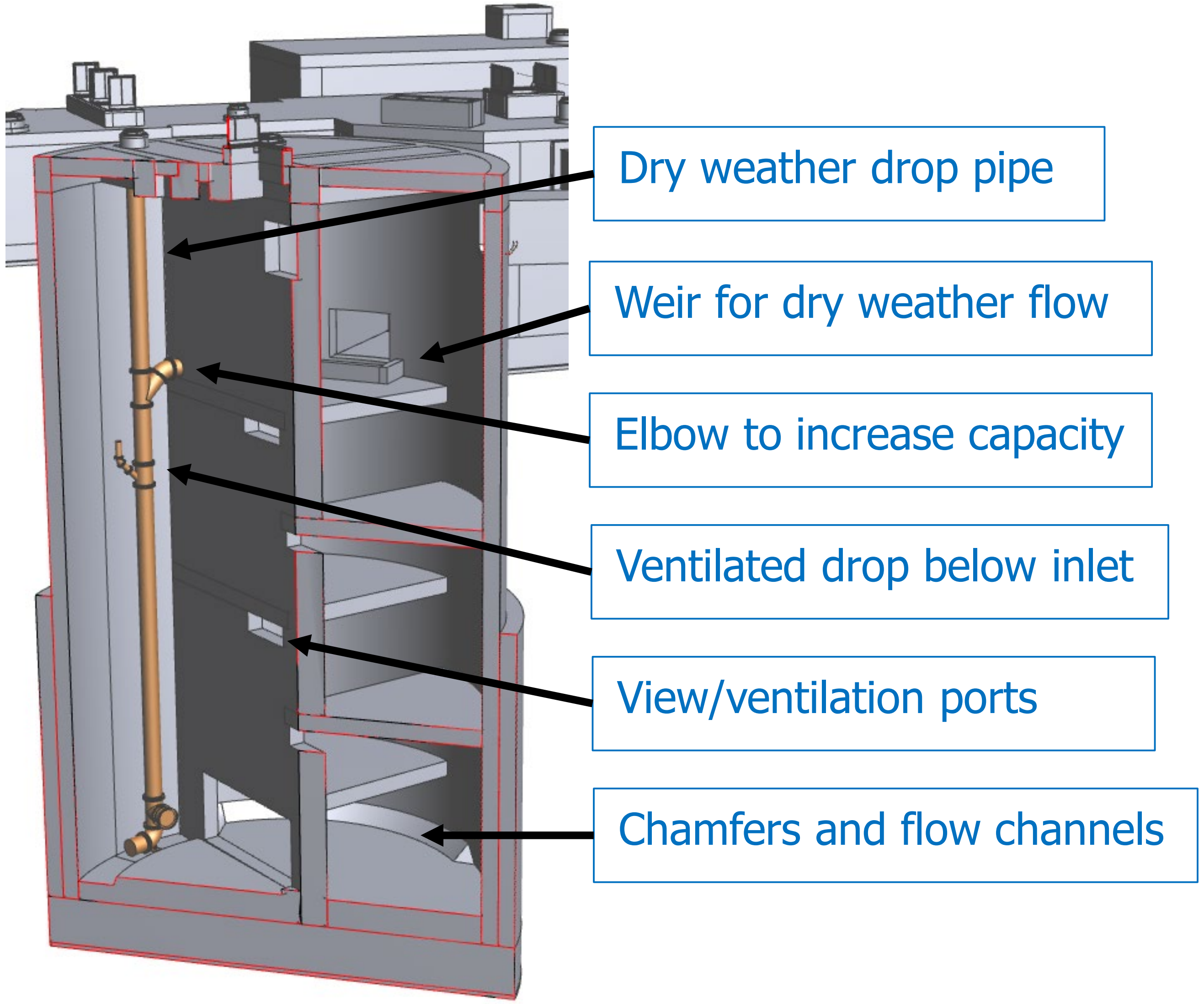
Case Study: NEORSD Baffle Dropshaft



5-year Storm: MGD
Peak Typical Year Storm: MGD
Average DWF: MGD

*Mass balance may not apply due to timing and attenuation through system.

Shaft DVT-2



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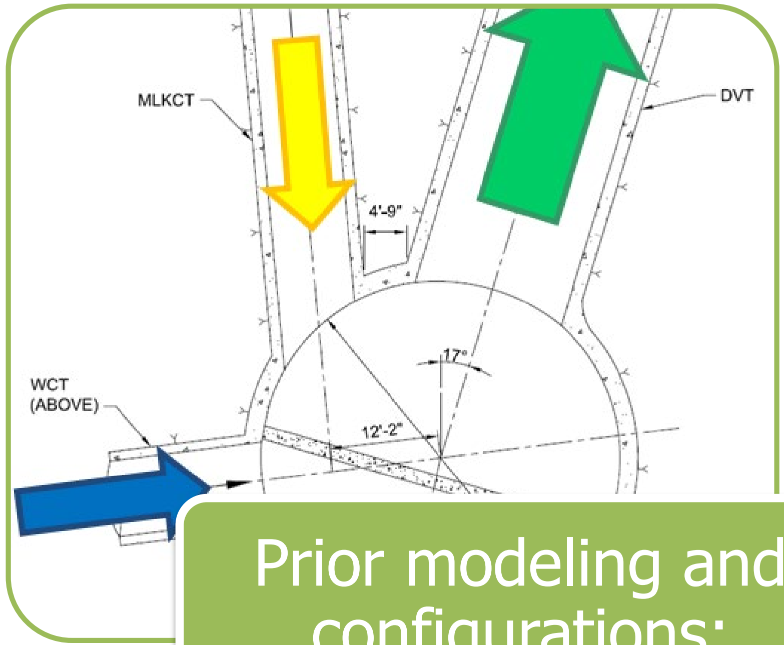
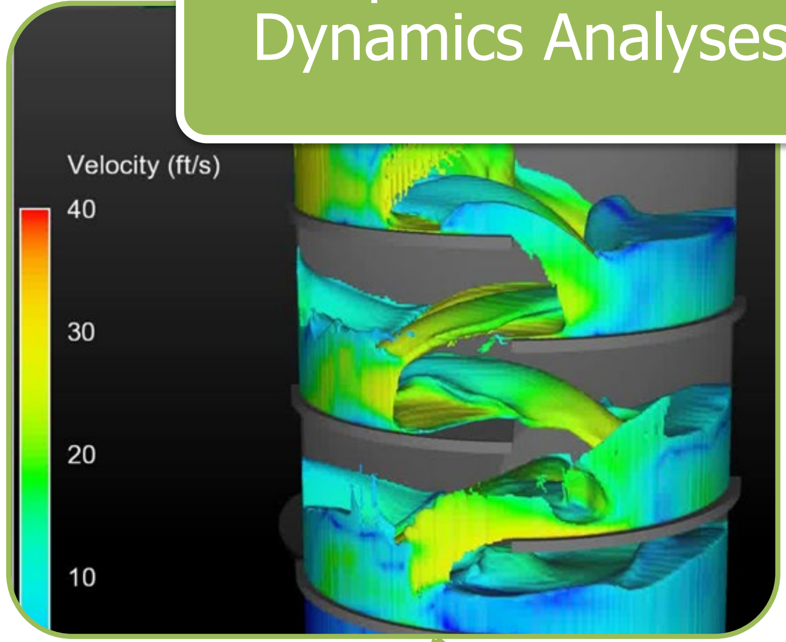
Case Study: NEORSD Baffle Dropshaft



Prior modeling and configurations: Hydraulic calculations



Computational Fluid Dynamics Analyses

Physical Modeling

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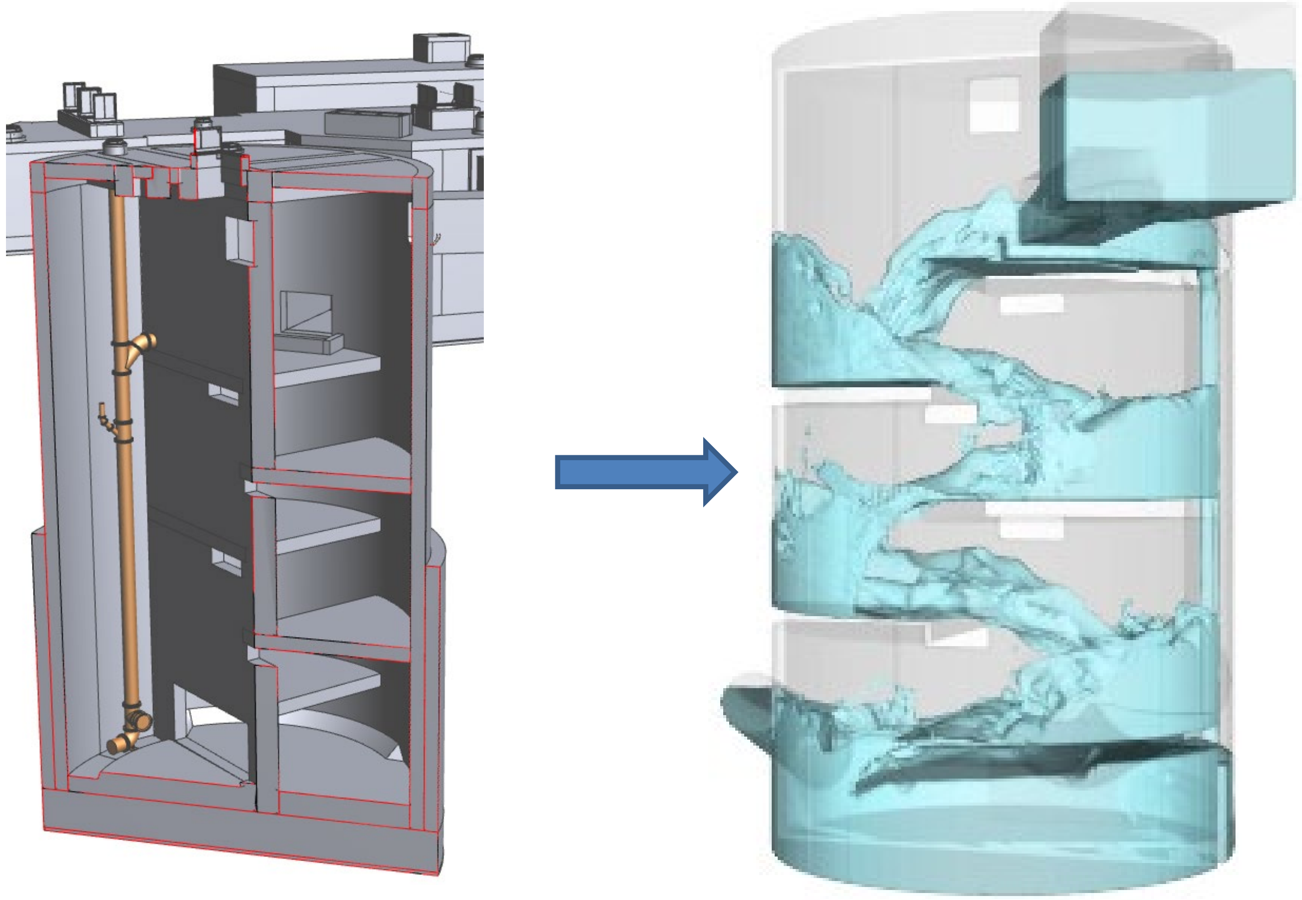
Case Study: NEORSD Baffle Dropshaft

- Reproduce geometry in CAD
- CAD available for full scale structure only
  - – Slight differences in configurations:
    - Weir height difference
    - Modification of entry flow location
    - Elbow on dry weather pipe
- Apply correct Boundary Conditions
- Flow rates
- Free discharge outflow



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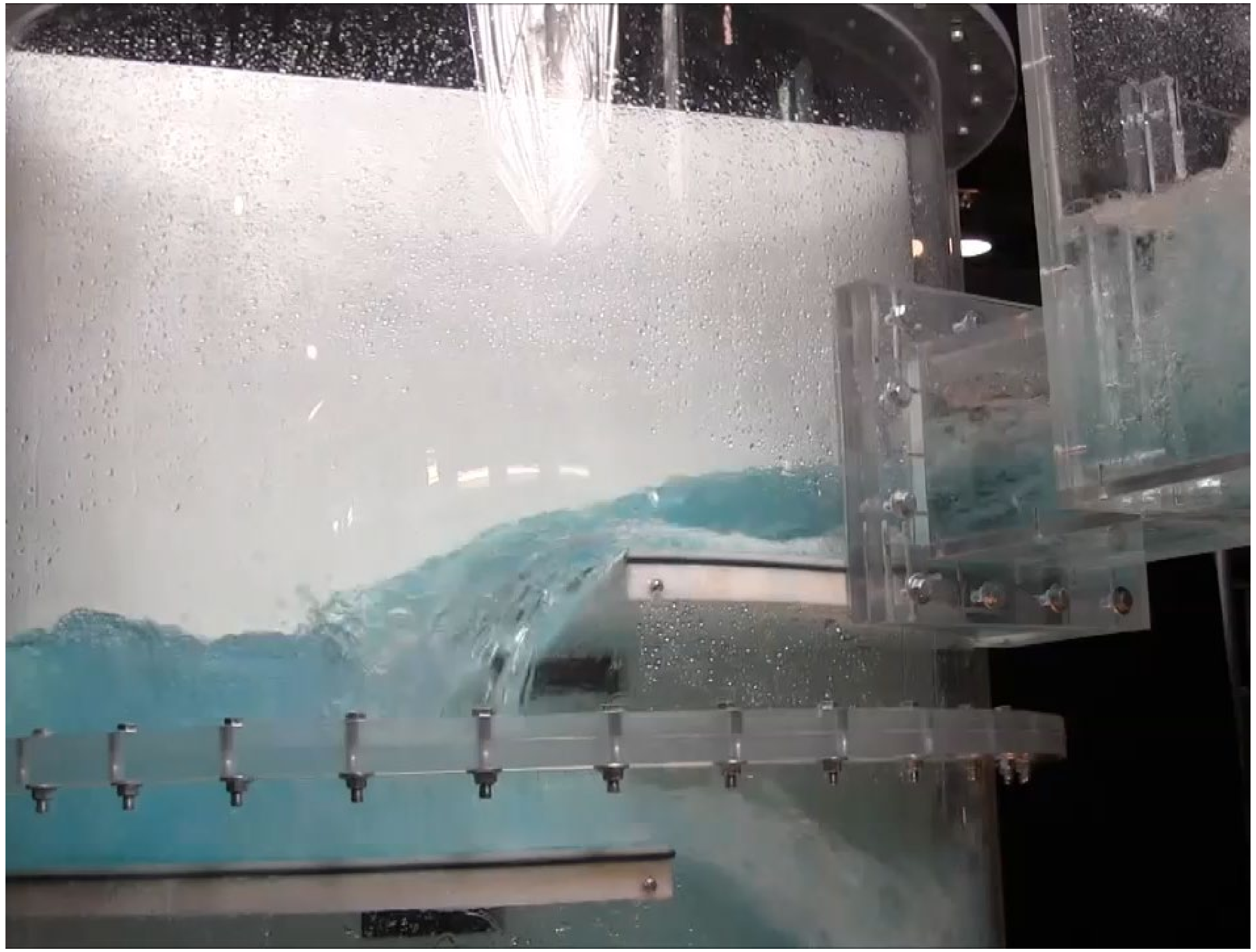
Case Study: NEORSD Baffle Dropshaft



Straight hydraulics: LES turbulence

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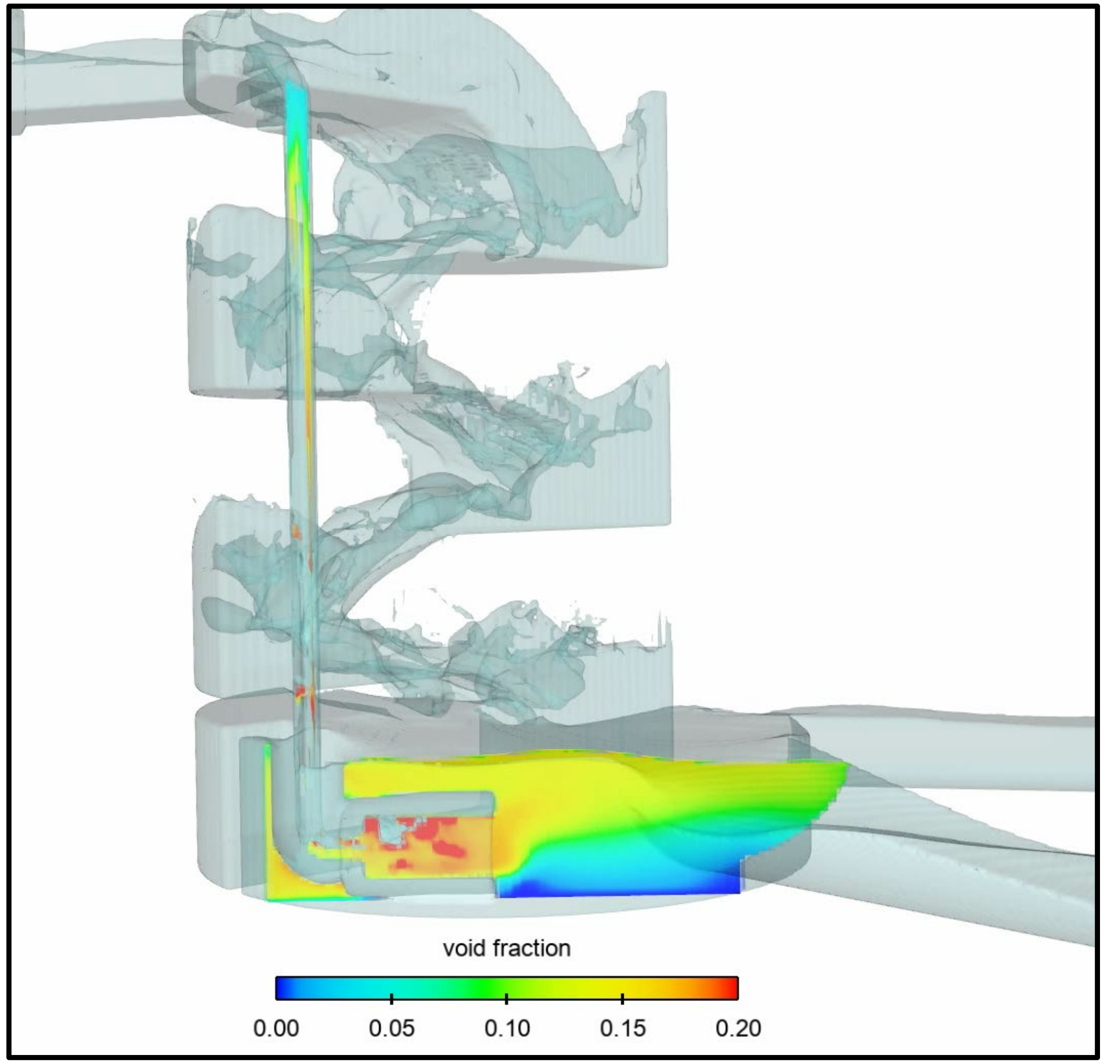

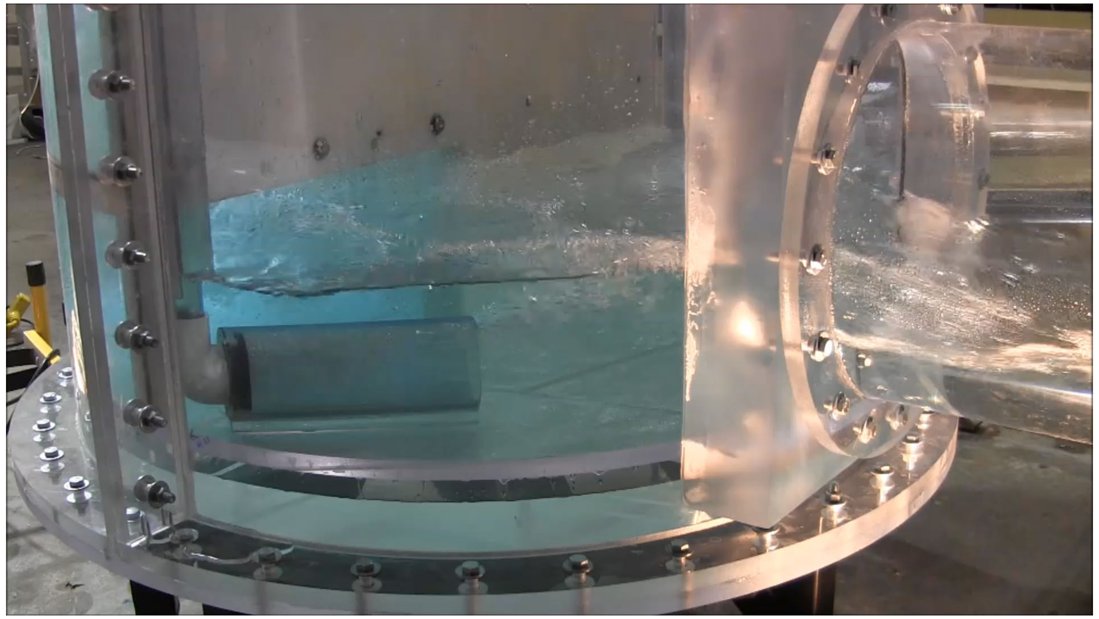

Air entrainment model turned on

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Summary / Air Entrainment in Dropshafts

Key Modeling Principles

- It all starts with good CAD
- Start simple, then sequentially add complexity
- Start with straight hydraulics
  - Viscosity, body forces, turbulence
  - Mesh sensitivity analyses – usually 10 cells across diameter
- Add complexity once hydraulics are in place!
  - Air Entrainment and transport
  - Bulking effects
  - Sediment transport

Summary / Key takeaways for modeling dropshafts

- Air entrainment CFD models can be used to guide dropshaft design, qualitatively at the very least
  - More work to be done!
- *Key physics* of system hydraulics coupled with air entrainment can be captured
- Appropriate level of complexity important
- While using the air entrainment model:
  - Sensitivity to turbulence modeling, grid size
  - Always good to calibrate against baseline physical model data
- Can be a valuable tool to explore the design/parameter space

Thank you!

Questions?