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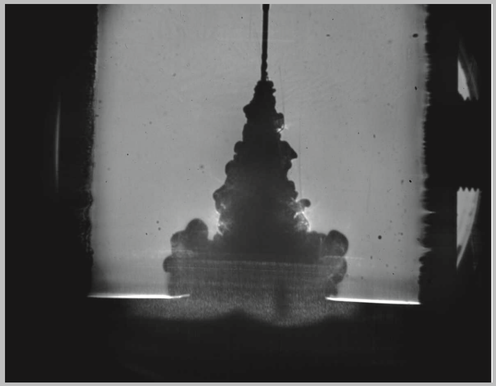

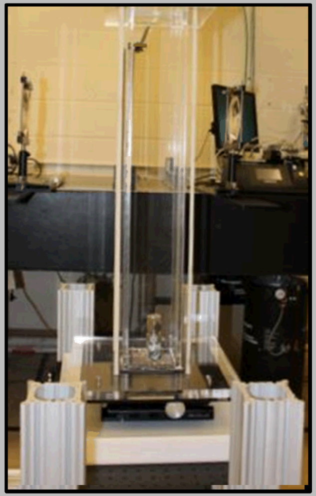

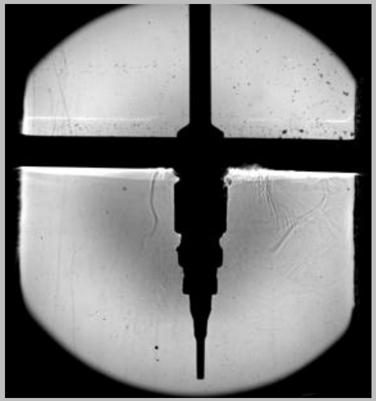

On the Controls of Mixing of Injected Water Jets with Brine in Salt Caverns: Scaled Flow Visualization Experiments

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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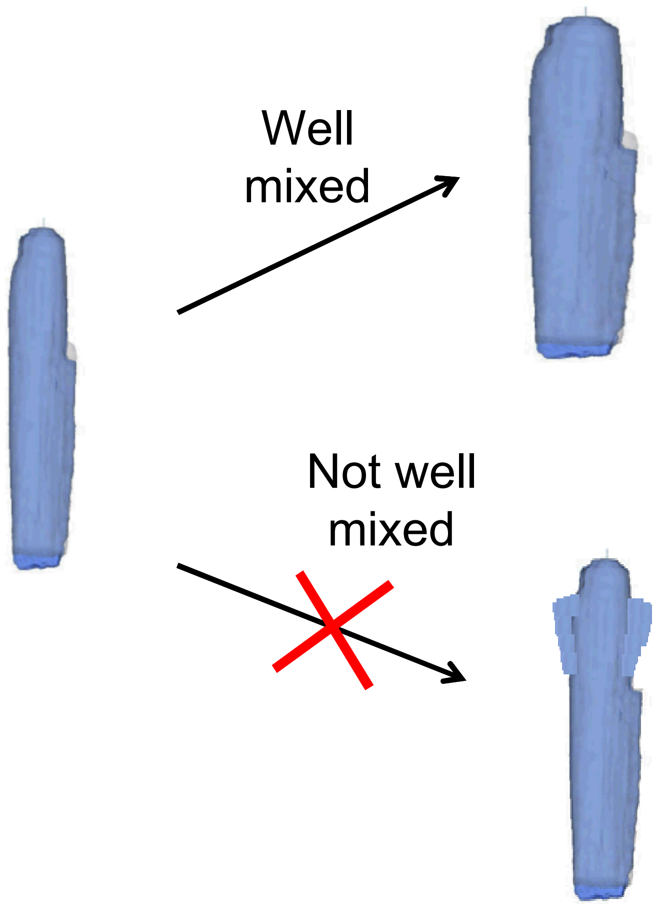
Problem Statement

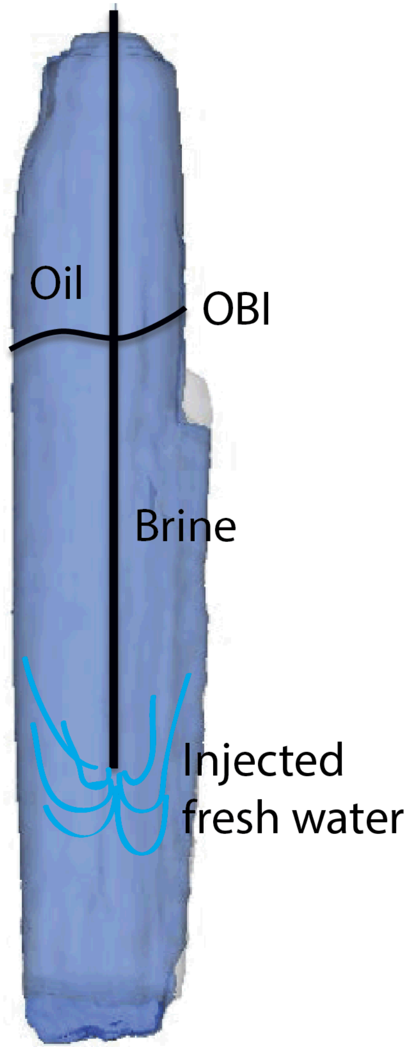
Under what conditions does fresh-water injection into a cavern containing saturated brine lead to complete mixing?



Complete mixing throughout the cavern leads to even dissolution of cavern walls above the injection point

Incomplete mixing has the potential to give the cavern "wings" at the oil-brine interface, causing potential salt fall

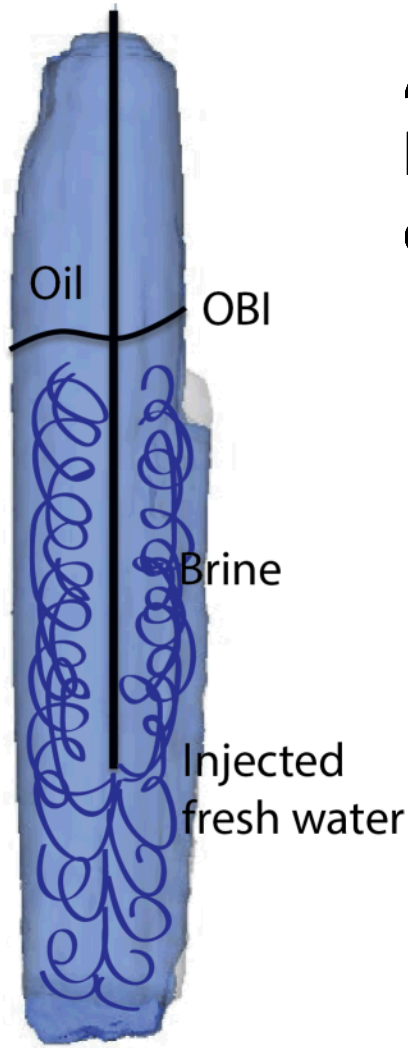
Problem Statement



Jet of fresh water entering a body of saturated brine and associated mixing

- "Negatively buoyant jet": buoyancy acts opposite to momentum
- Different operation and leaching scenarios may involve:
  - Variety of string depths for water injection and brine or oil production
  - Usually slender cavern geometries
  - Initial injected water chemistry and physical properties and salt cavern chemistry
  - Possible string breakages

Field Data



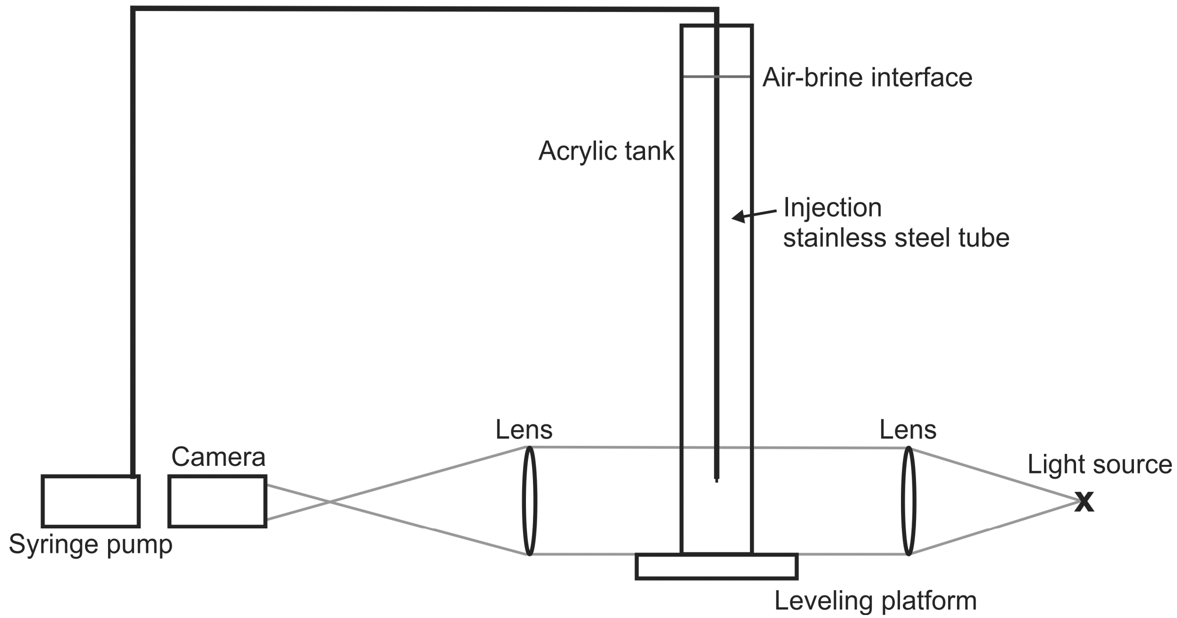
At high flow rates in high-aspect ratio caverns, brine and fresh water appear to completely mix on the timescale of leaching

- Field observations and SANSMIC simulations of remedially leached caverns (SAND2013-7078) show what appears to be well-mixed leaching

Previous Experimental Work

- SPR experimental and modeling work several years ago showed the potential for incomplete mixing and formation of a cap of fresh water at the brine-oil interface
- **Goal of this project is to determine conditions that govern poorly- to well-mixed conditions, to avoid a freshwater cap during SPR operations**

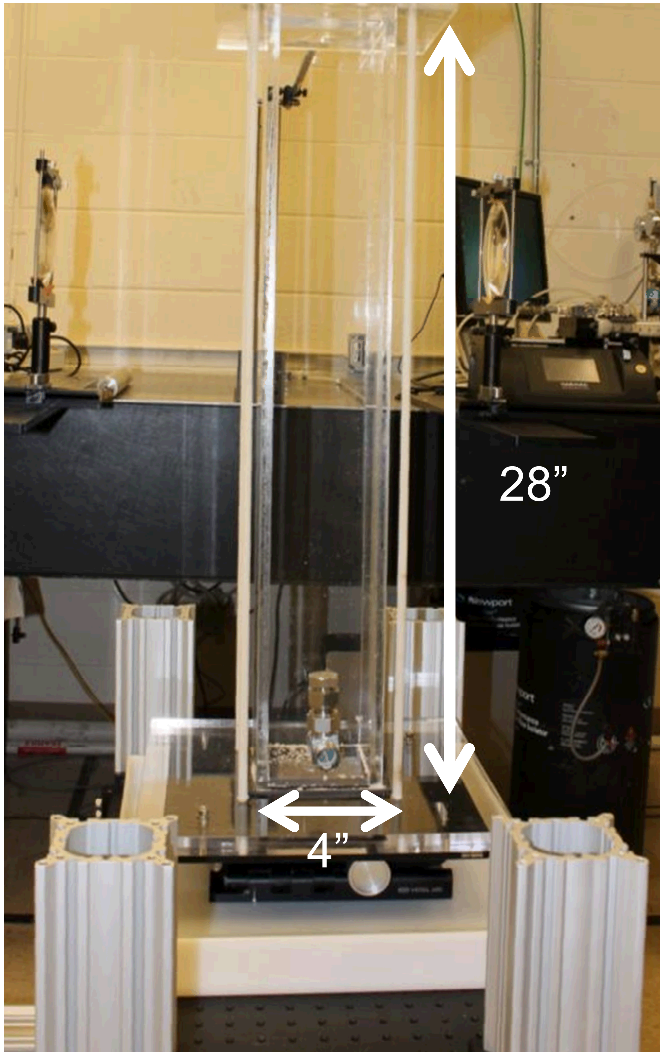
Tank-Scale Mockup of an SPR Cavern



Parameters that can be varied:

- Flow rate, nozzle diameter
  - **Momentum**
- Distance from nozzle to tank bottom
  - **Effect of impingement**
- Density difference
  - **Buoyancy**
- Salt type
  - **Diffusion constant**

Experimental Design

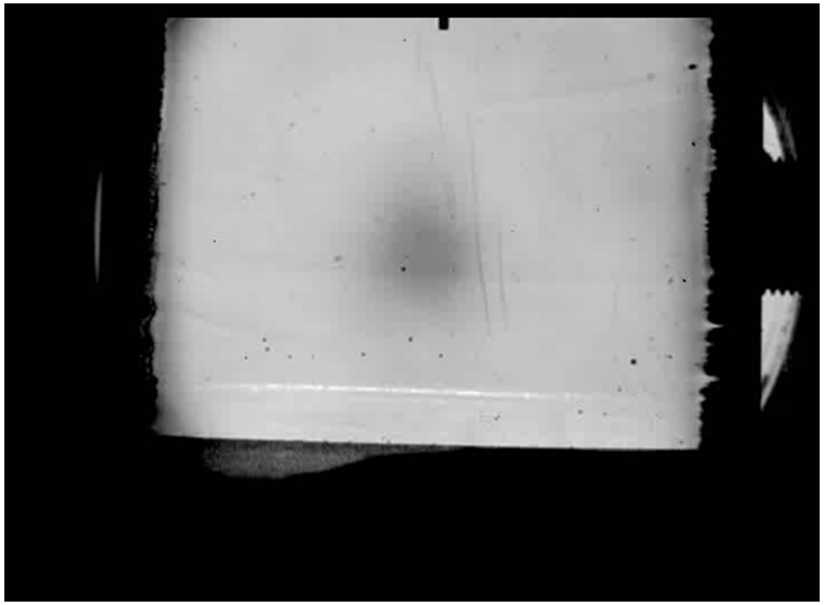


- **Original Hypothesis:**
  1. If the fresh water jet spreads to fill the entire plan view (4” x 4”) then maximum mixing will occur.
  2. Incomplete mixing leading to a layer of fresh water at the top of the tank will occur at a some flow rate below 1.
- **Experimental Method:**
  A. Observe the plume width versus time to determine flow conditions that lead to a plume that fills the plan view of the tank.
  B. Determine conditions that lead to a fresh water cap.
  C. Correlate A. and B.

First Round of Experiments

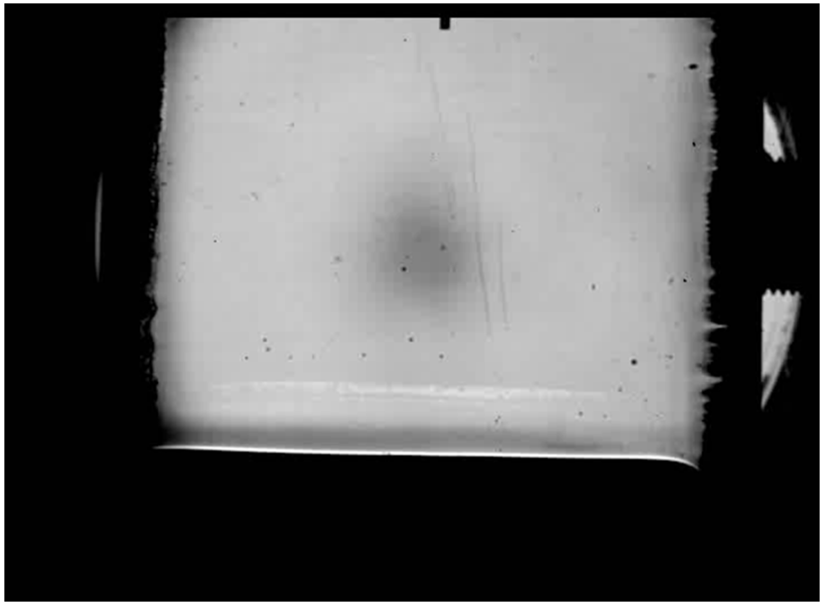
Observe bottom of the tank, determine controls on plume spreading

Non-impinging



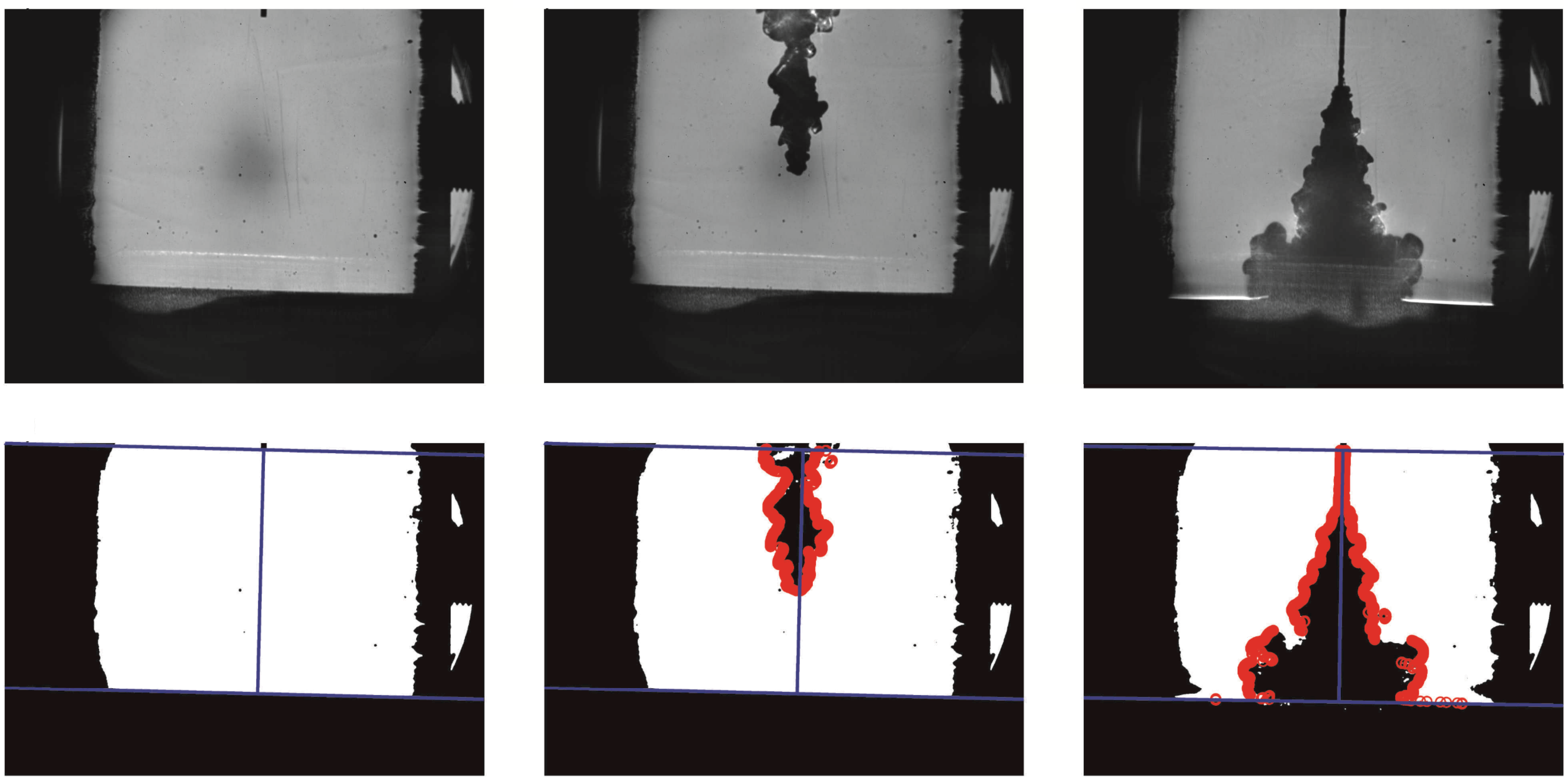
Nozzle is 3” from bottom
Height of brine column: 26”
Orifice diameter: 0.06”
Flow rate: **52.5 ml/min**
Velocity: 0.5 m/sec

Impinging



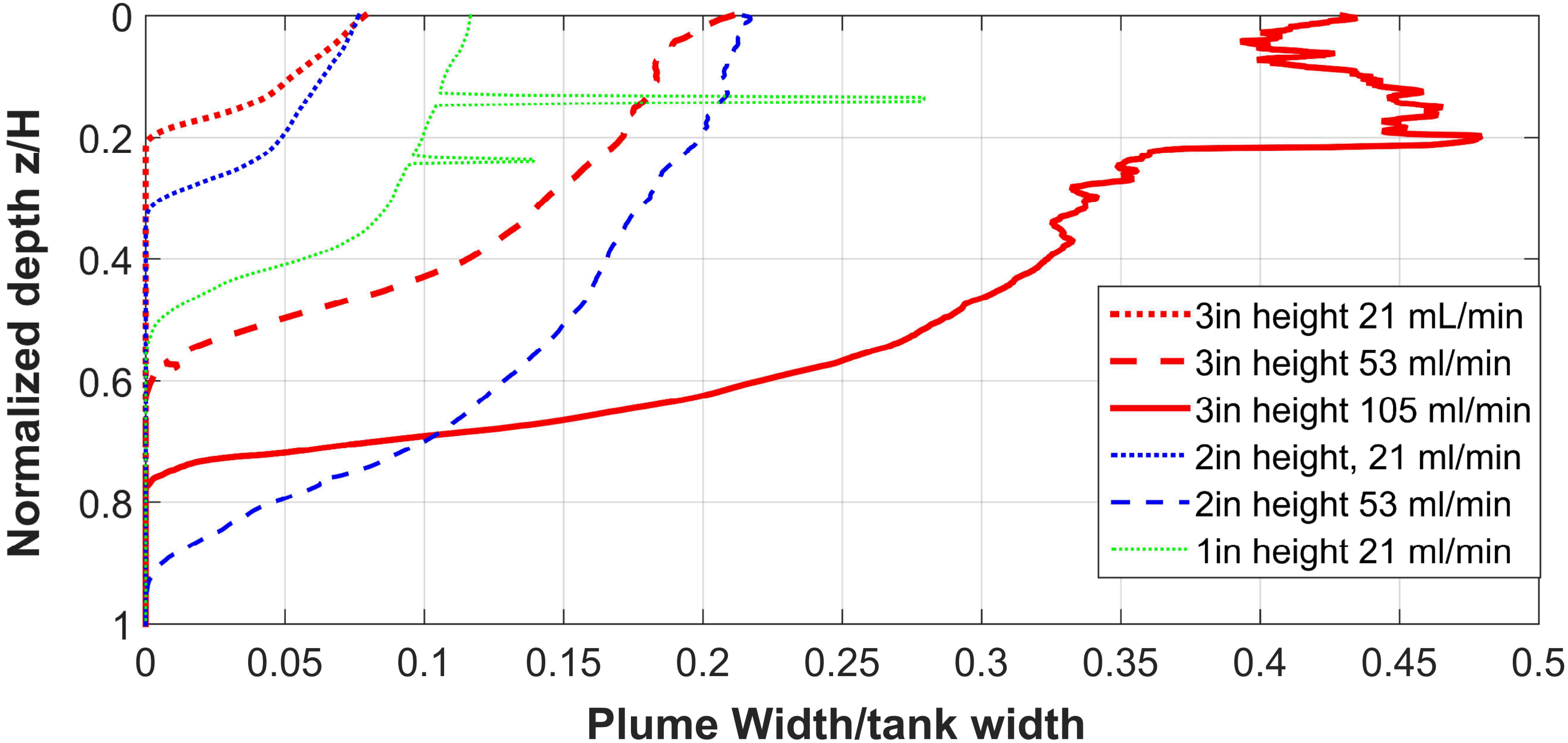
Nozzle is 3” from bottom
Height of brine column: 26”
Orifice diameter: 0.06”
Flow rate: **210 ml/min**
Velocity: 2 m/sec

Image Processing



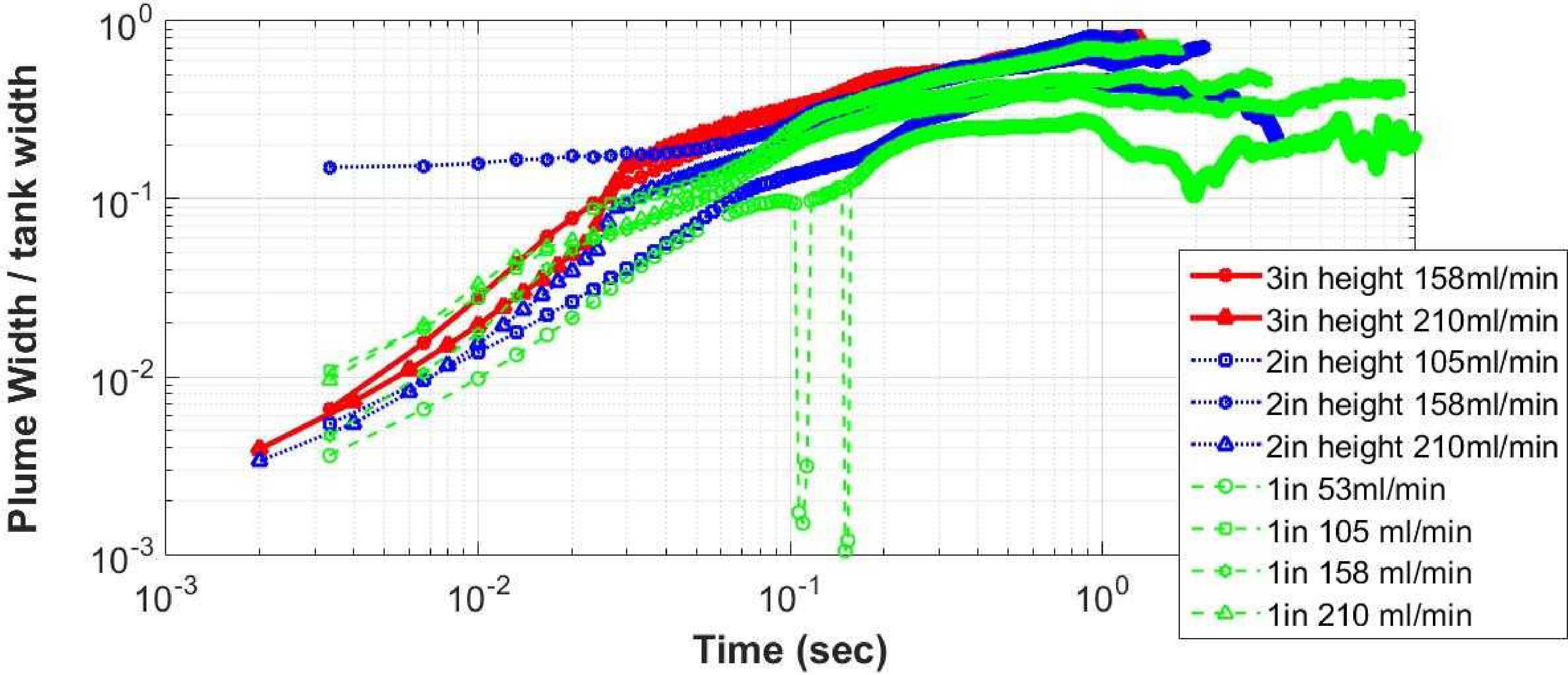
- Image processing determines the plume width versus time
- Scripts automatically threshold and measure plume width for every frame

Results for Non-impinging Case



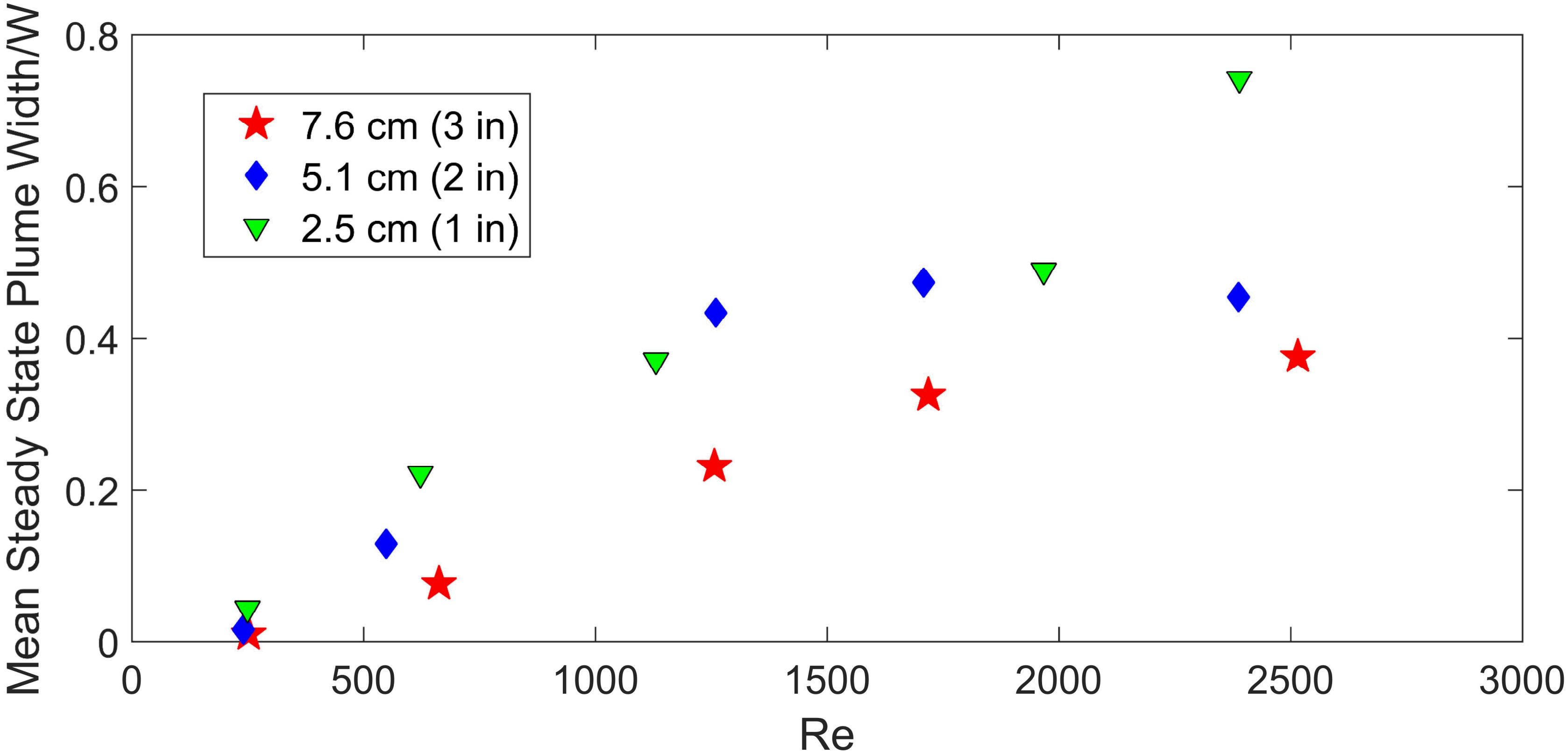
- Time-averaged plume width is well defined and can be plotted versus distance from the orifice
- Penetration depth depends on flow rate in contrast to previous work (Webb) on neutrally buoyant jets
    - Reasonable given that flow rate is now opposing buoyancy

Results for Impinging Case



- For greater nozzle heights and flowrates, plume appears to continue to spread with time until it hits the vertical wall
- Unclear whether this is an appropriate metric

Combing Impinging/Non-impinging

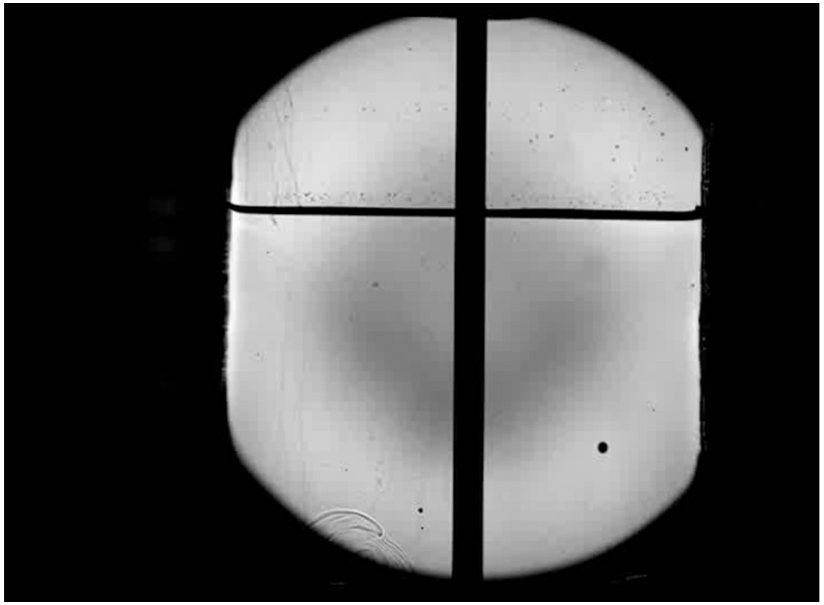


Time averaged and spatial averaged plume width normalized by tank width as f(Re)

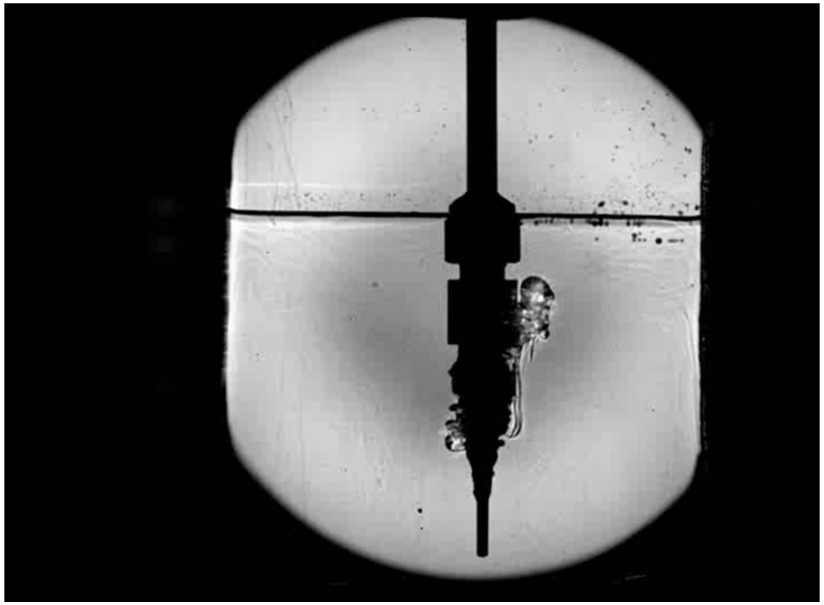
Second Round of Experiments

Observe air-brine interface (top of the tank), look for a fresh-water cap

Nozzle 3” above base of tank



Nozzle near air-brine interface

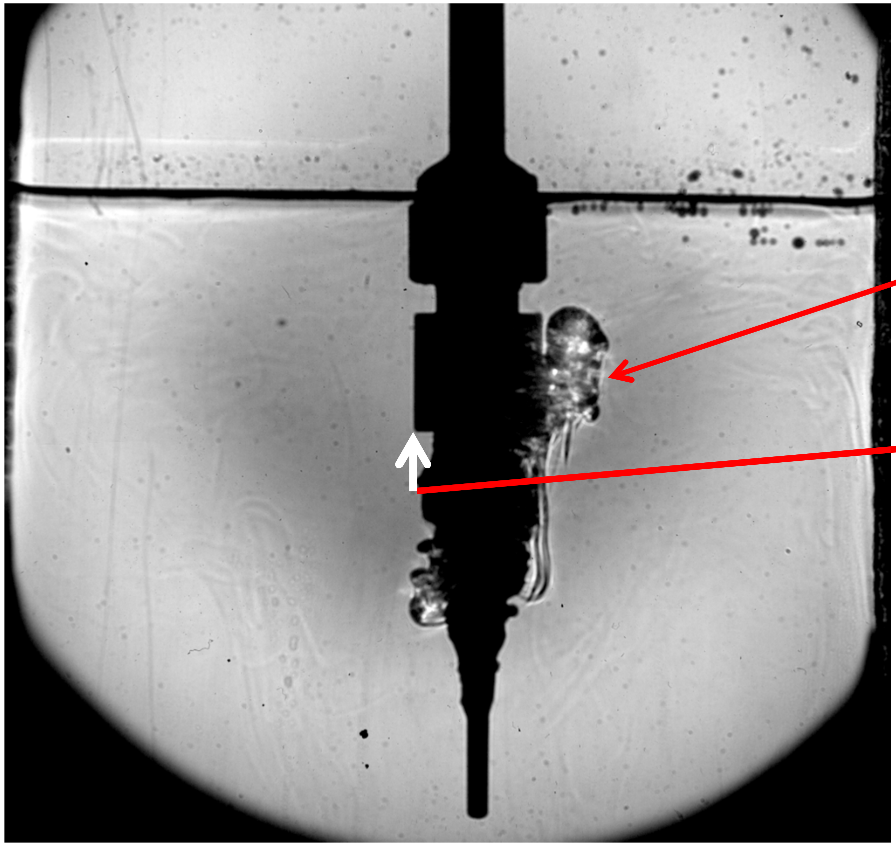


Nozzle is 3” from bottom
Height of brine column: 26”
Orifice diameter: 0.06”
Flow rate: **1 ml/min**
Velocity: 0.01 m/sec

Nozzle is near air-brine interface
Height of brine column: 26”
Orifice diameter: 0.06”
Flow rate: **1 ml/min**
Velocity: 0.01 m/sec

Boundary-Layer Detachment and Mixing

Whether freshwater cap forms may mostly depend on whether freshwater detaches from the boundary layer on the brine string

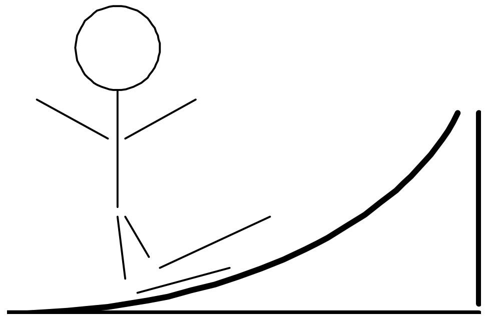


Plume of fresh water detaching from the pipe

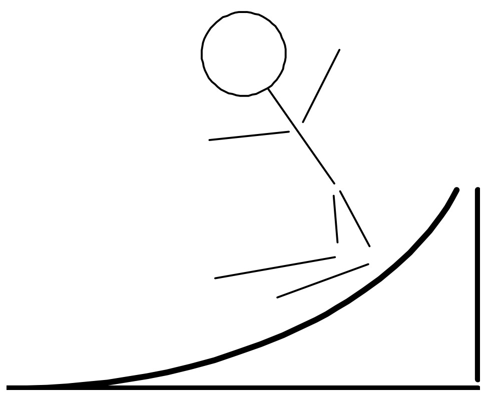
Points of positive curvature are locations of detachment

Why does detachment occur

Think about a skier going off a ski jump



Skier will detach from the ground at end of the ramp due to momentum



Going the other way, skier will remain in contact with the ground, nothing moving the skier away from the surface

Conclusions and Next steps

- **May have been hammering the wrong nail!**
- Instead of continuing down path of looking at jet spreading and mixing, it appears we should be focused on understanding boundary-layer detachment
  - Returning plume width versus the string diameter
  - Asperities on the string
  - Width of the buoyant plume resulting from an asperity of a given size
  - Characteristics of the buoyancy-driven flow
- Understand detaching boundary layers flowing along the outside of axisymmetric pipes
- Concern of mixing in very wide caverns is still valid, deserves a look at some point in the future.