Simulation of the Dynamics of Perforating for a Selected Charge and Subsequent Analysis of Tunnel Cleanup Based on the Direction of Gravity

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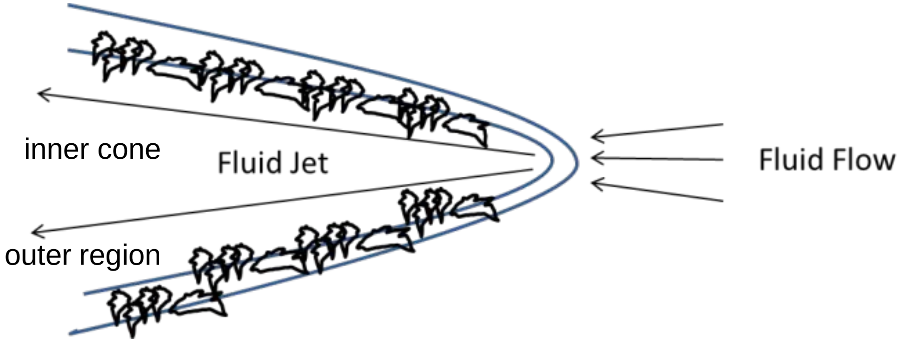
Previous Work

- IPS 2012, OTC San Antonio 2012, September 2013 JPT
  - the perforation tunnel can create a localized jet of incoming flow
- This localized jet is generally Kelvin Helmholtz unstable so that the flow separates and is turbulent
  - The inner cone is at an experimentally measured angle and is turbulent
  - The outer region is quiescent
- Crushed zone formed from CTH: 0.2 – 0.5 cm



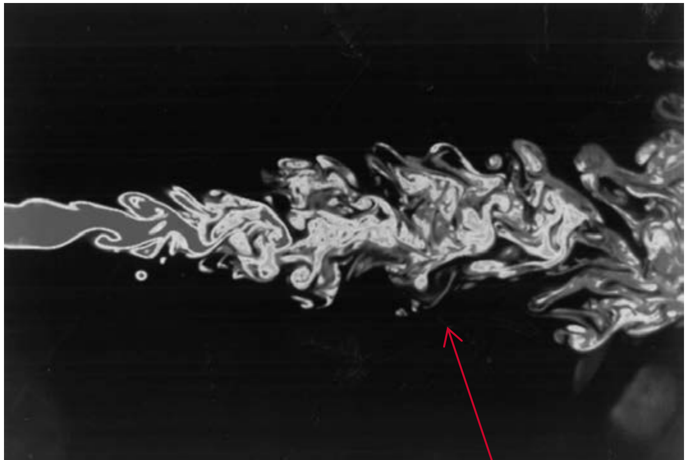
This Presentation Concerns Stability

- Fluid instability is ubiquitous and is what drives flow away from quiescence
- Perforation cleanup is a fluid problem
- Most instabilities start linearly with exponential growth rates

$$\frac{\partial \delta}{\partial t} = \gamma \delta; \quad \delta \sim \delta_0 \exp(\gamma t)$$

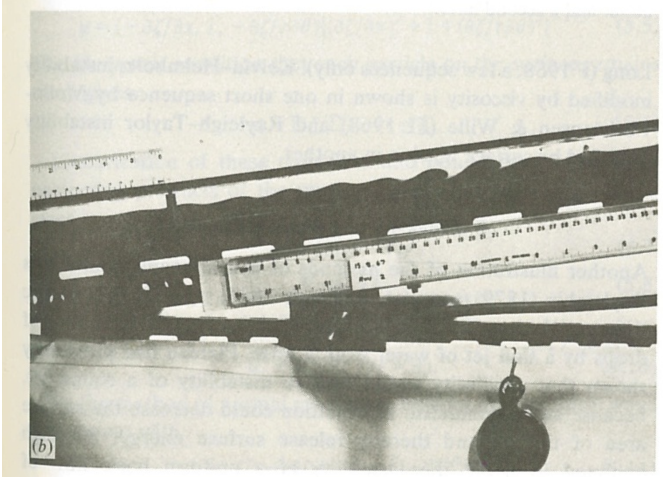
- Nature wants to lower free energy and to eliminate gradients: this is how instabilities are born
- Many instabilities occur at interfaces
- Linear instabilities grow until nonlinear physics takes over
  – Wave breaking
  – Mode overlap
  – Turbulence
- Concern here is two instabilities (a Tale of two Stabilities)
  – Velocity gradients: Kelvin-Helmholtz
  – Density gradients under acceleration: Rayleigh-Taylor

Kelvin-Helmholtz Instability



R. R. Prasad and K. R. Sreenivasan, 1990

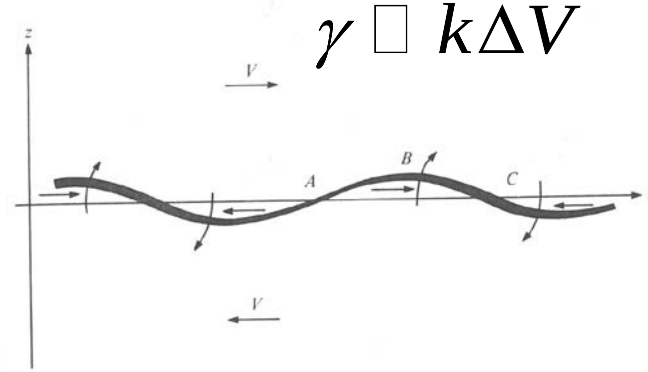
Transition to Turbulence



Fluids slide past each other (Thorpe, 1968)

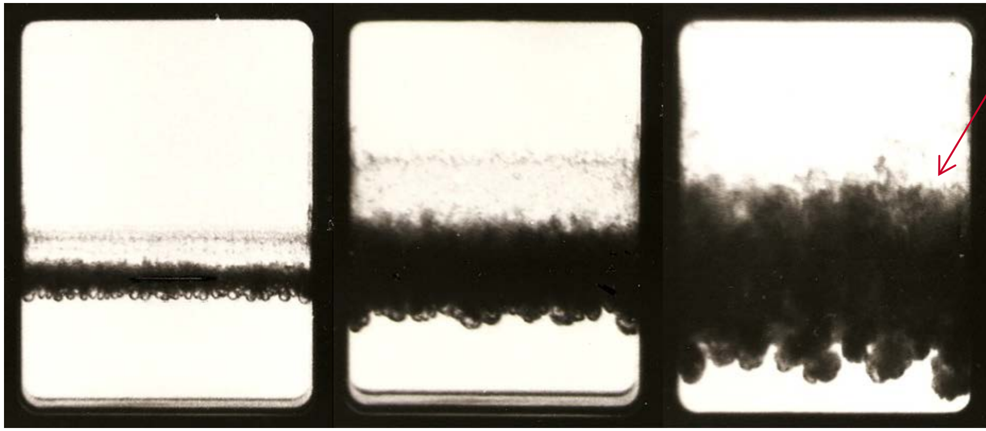
4 KELVIN–HELMHOLTZ INSTABILITY 15

γ □ $k\Delta V$



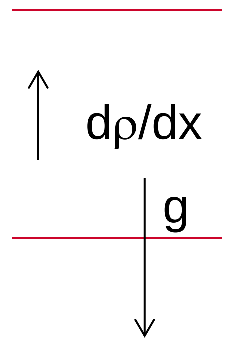
Rayleigh-Taylor (RT) Instability

Transition to Turbulence



Photographs taken at 33, 53 and 79 ms of RTI in an accelerating tank. The density ratio is 8.5 to 1.(Youngs 1989).

Continuous density gradient

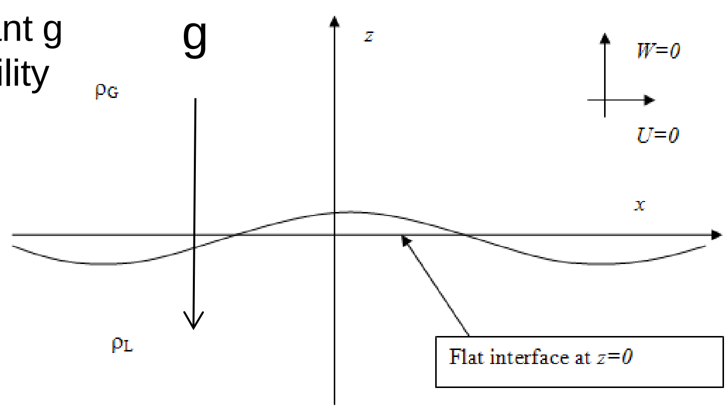


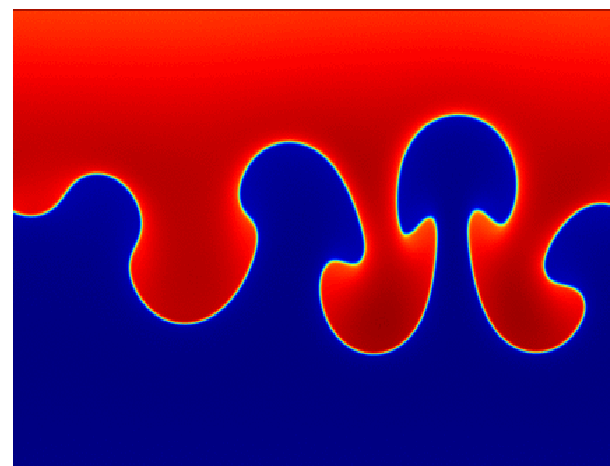
$$\gamma \sim \sqrt{\left|\frac{d\rho}{\rho dx}\right| g}$$

Interface Constant g Instability

$$\gamma = \sqrt{Akg}$$

$$A = \frac{\rho_G - \rho_L}{\rho_G + \rho_L}$$





Xiaowen Shan and Hudong Chen (1993)

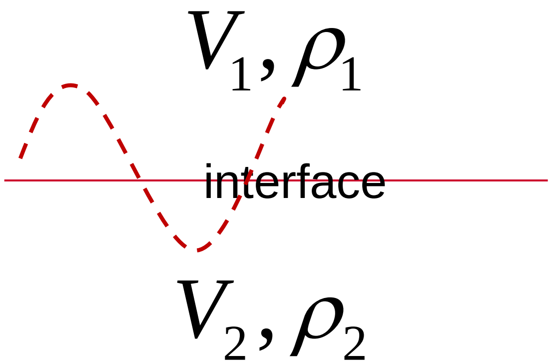
msec time scale
for cleanup applications

Combined KH and RT Instability: Instabilities do not necessarily add

$$\gamma = -k(\alpha_1 V_1 + \alpha_2 V_2) \pm \left[gk(\alpha_1 - \alpha_2) - k^2 \alpha_1 \alpha_2 (V_1 - V_2)^2 \right]^{1/2}$$

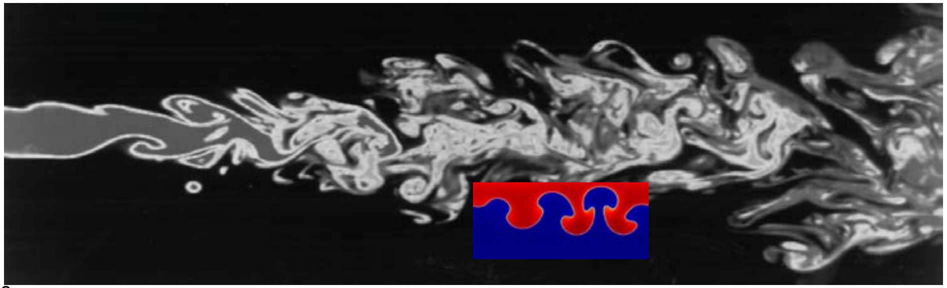
$$\alpha_1 = \frac{\rho_1}{\rho_1 + \rho_2}$$

$$\alpha_2 = \frac{\rho_2}{\rho_1 + \rho_2}$$

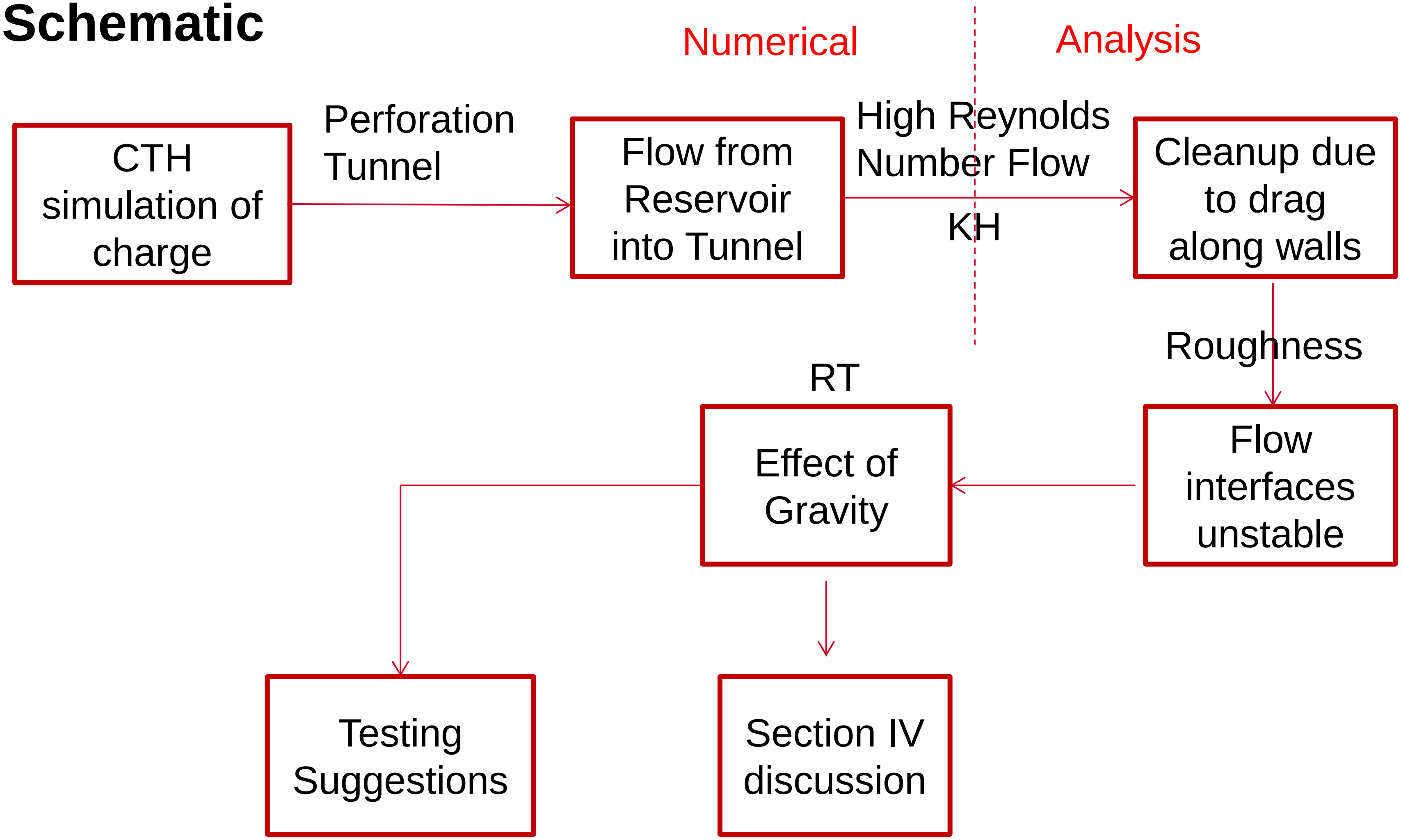


Li, Shengtai and Hui Li. 2006

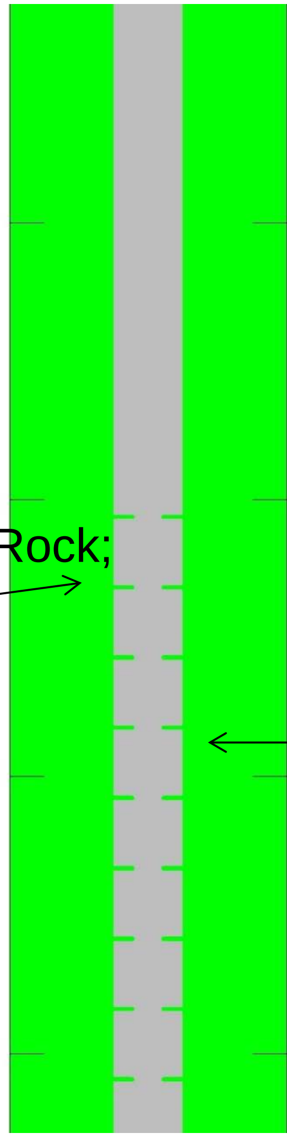
KH stabilizes RT and vice versa: How interfaces are stabilized depends on interaction of two instabilities



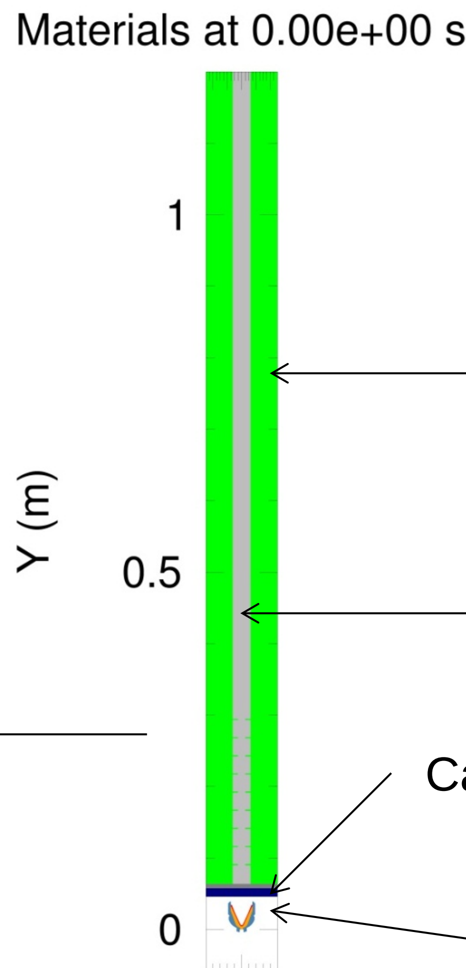
Schematic


Numerical
Analysis
CTH simulation of charge
Perforation Tunnel
Flow from Reservoir into Tunnel
High Reynolds Number Flow
KH
Cleanup due to drag along walls
Roughness
Flow interfaces unstable
RT
Effect of Gravity
Testing Suggestions
Section IV discussion

CTH Setup



Effective Flow through Rock; Target Simulated By Ring slices



5000psi water

Sand Target

Casing, scallop, and bore fluid (water

11.2 g Charge

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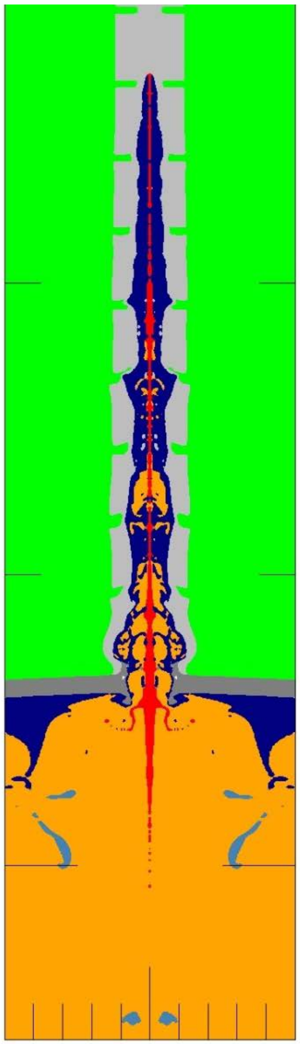
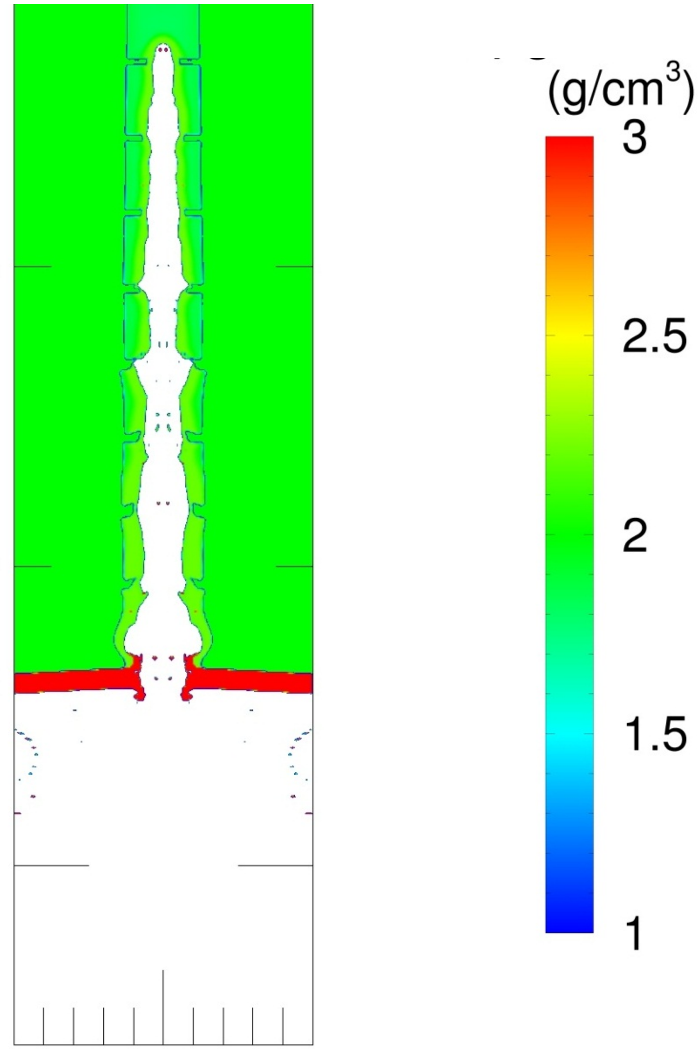
Perforation tunnel is formed and charge materials are removed from simulation: Tunnel forms in .12 ms

materials



Material
Removed

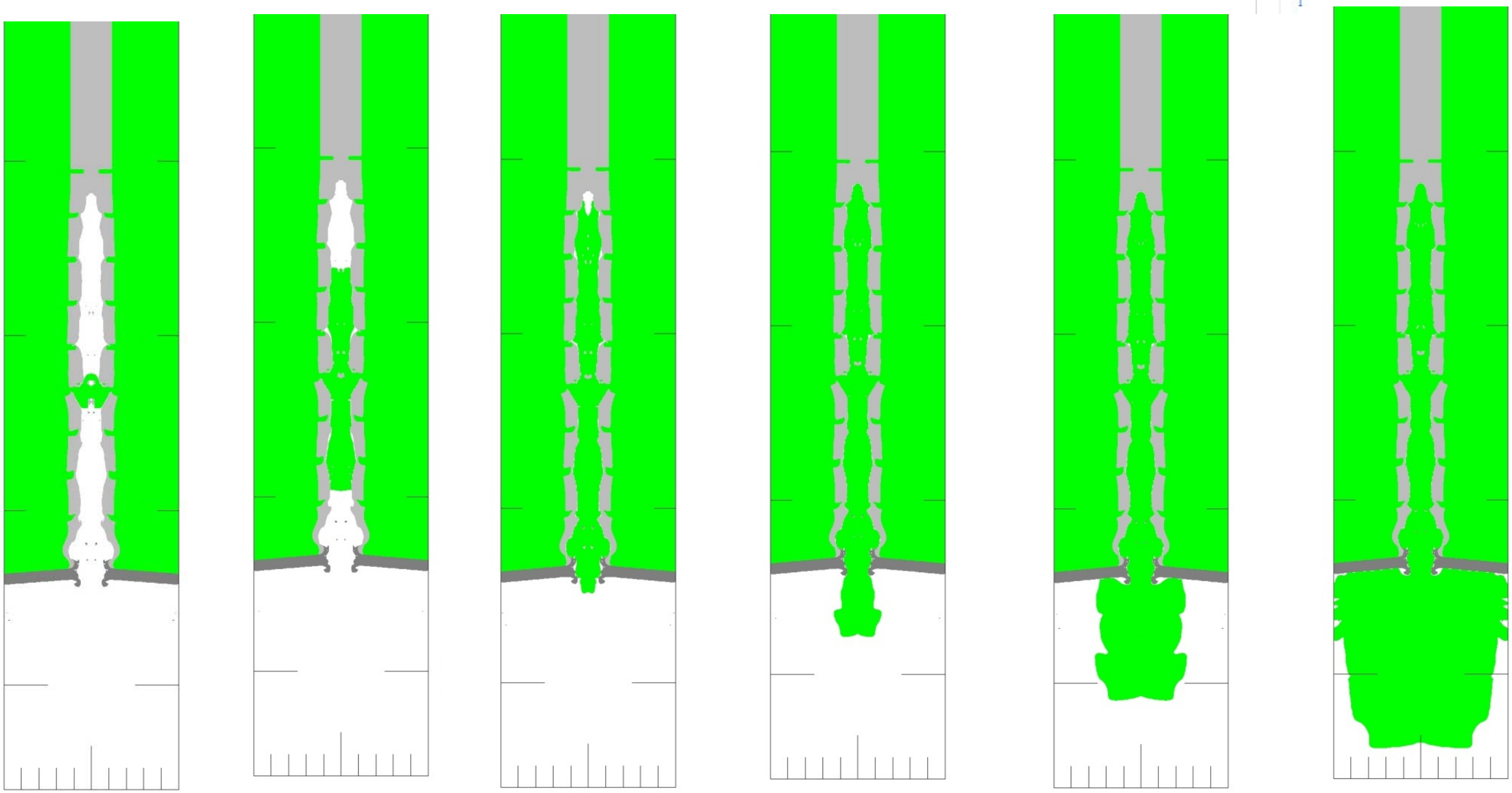
density



Fluid flows into perforation tunnel

Flow

.14 ms .155 ms .165 ms .17 ms .175 ms .18 ms



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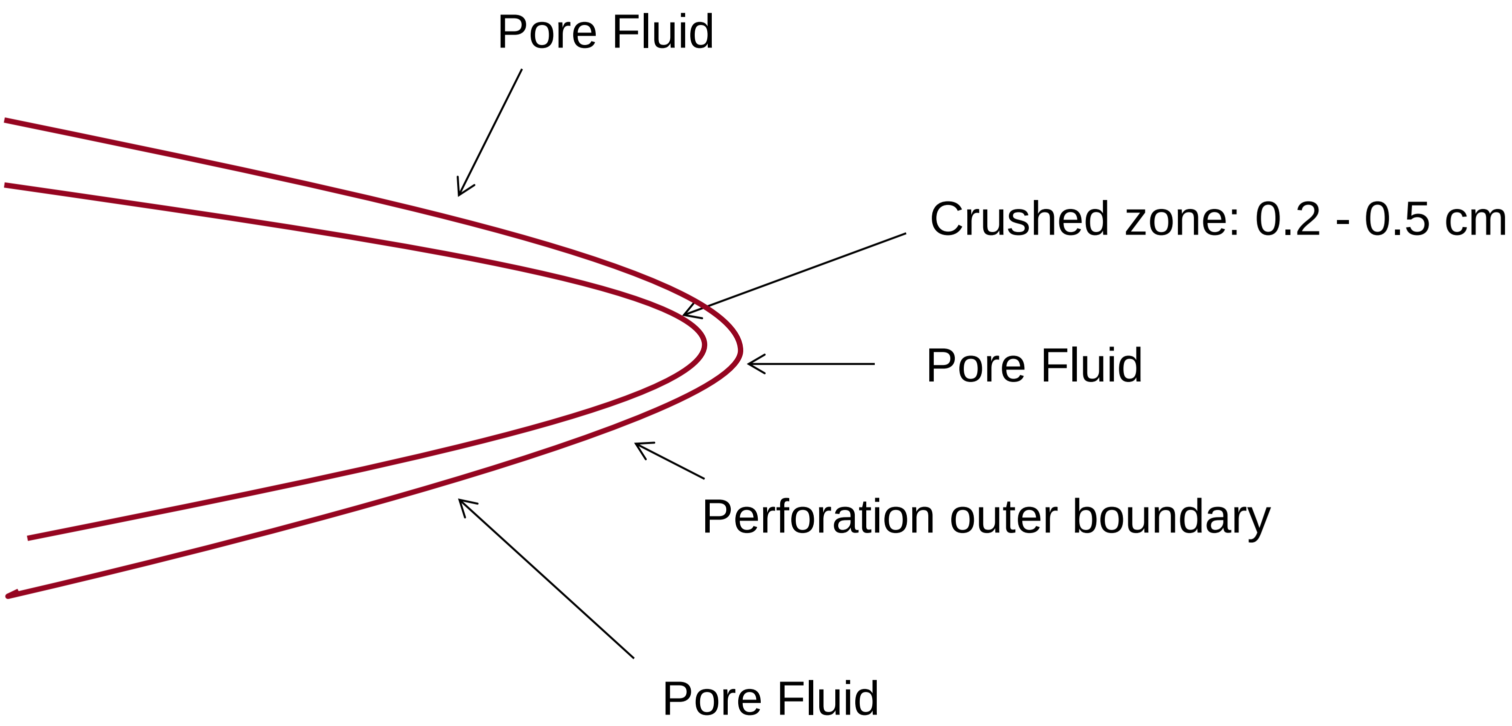
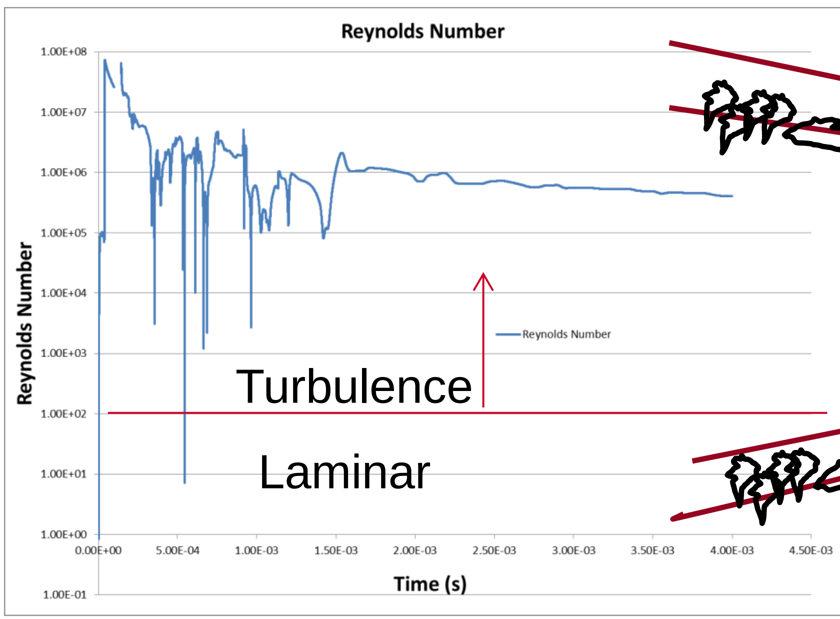
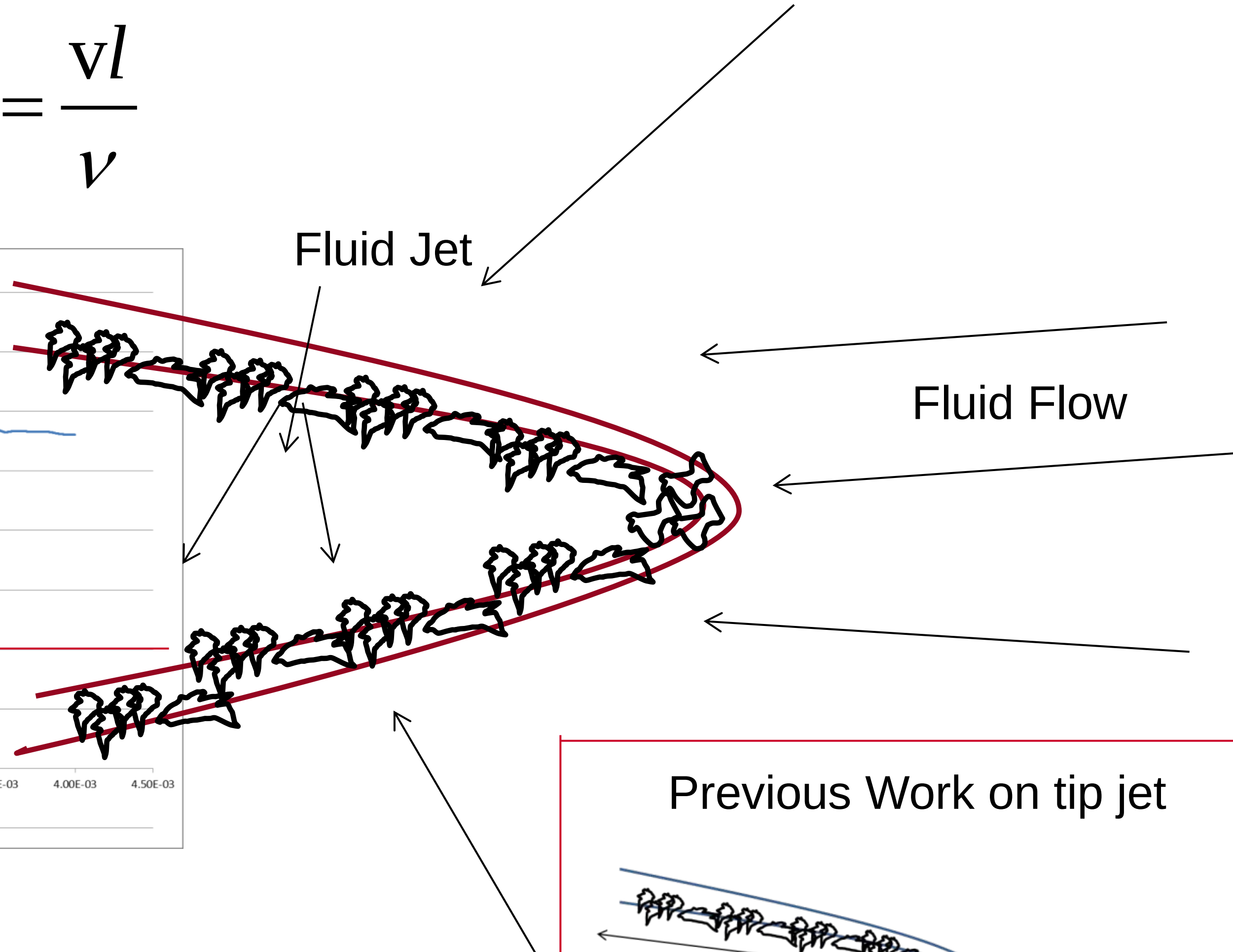
Perforation Cavity/Tunnel



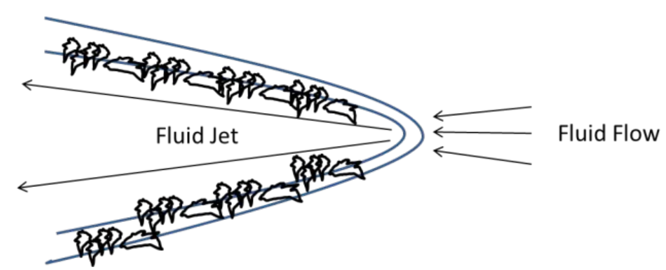
Simulation shows that Initial flow is Turbulent

Reynolds Number $R = \dfrac{\mathrm{v}l}{\nu}$





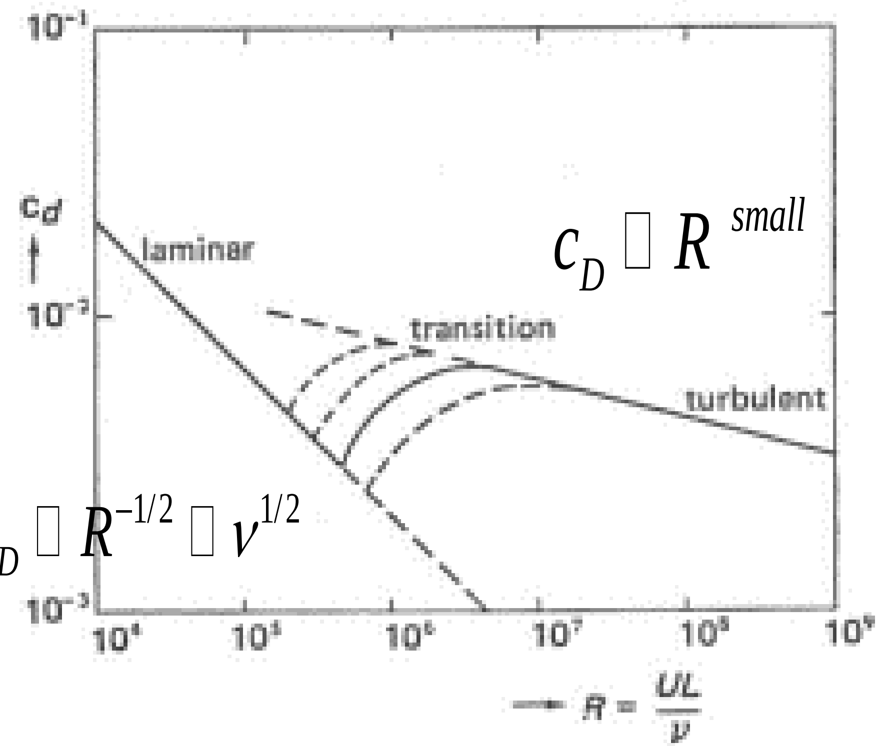
Previous Work on tip jet



Drag is Key to Cleanup by Jet

- Drag is basically the resistance to flow along a surface
- The greater the drag, the more material is pulled away from walls
- *Increased drag promotes cleanups by flow along walls*
- Low R drag is viscous dominated
  - Drag coefficient goes up with viscosity
- High R drag is turbulence dominated
  - Drag coefficient has little viscosity or Reynolds Number dependence
  - Wall dependence shifts to roughness of rock surface
- Turbulent drag is bad for aerodynamics, but good for cleanup
  - Also good for mixing of particulates
- Instead of drag reduction, drag enhancement?

$$F_D = \frac{1}{2} c_D \rho \, v^2 A$$

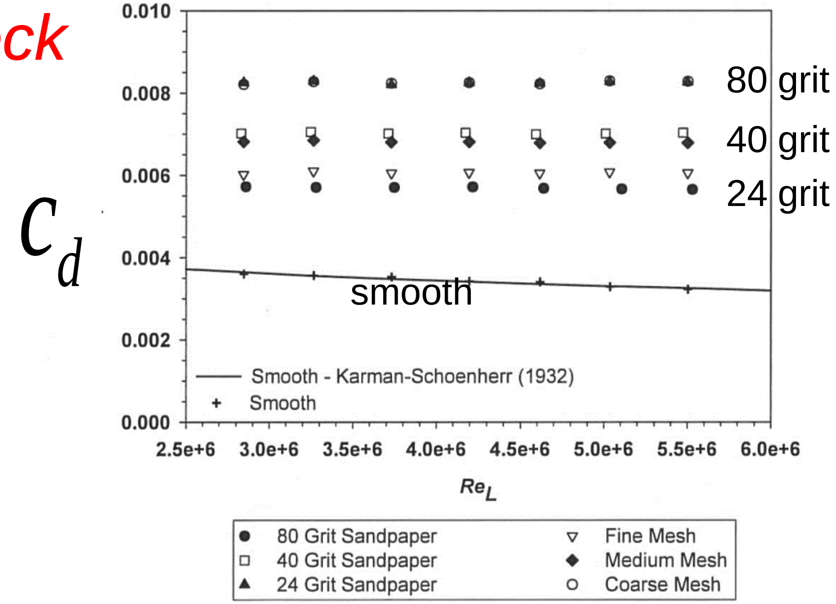


$c_D \propto R^{small}$

$c_D \propto R^{-1/2} \propto \nu^{1/2}$

Roughness Affects Drag

- When flow eddies approach size of roughness length, then drag is affected
- Turbulence implies smaller and smaller eddy size
- Some theories say the effect is logarithmic
- *Suggests charge tailoring to rock based on coefficient*



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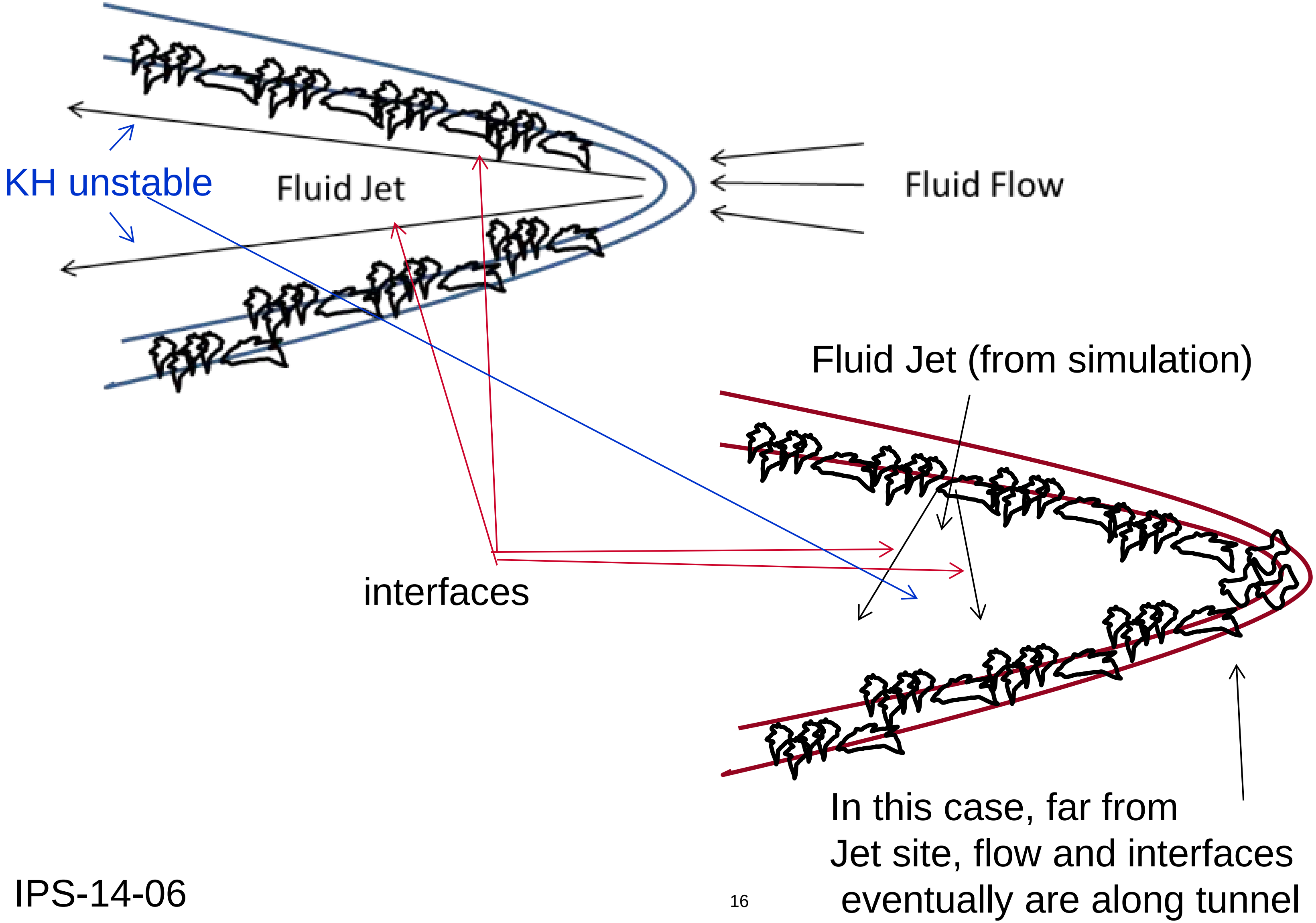
Effect of Gravity on Perforations

For example,
gravity-related sanding studies to better understand the effects of perforating and fracturing in horizontal wells.

Perforation Specific: Kelvin-Helmholtz drive unstable jets; Fluid interfaces are focus of Rayleigh-Taylor instabilities



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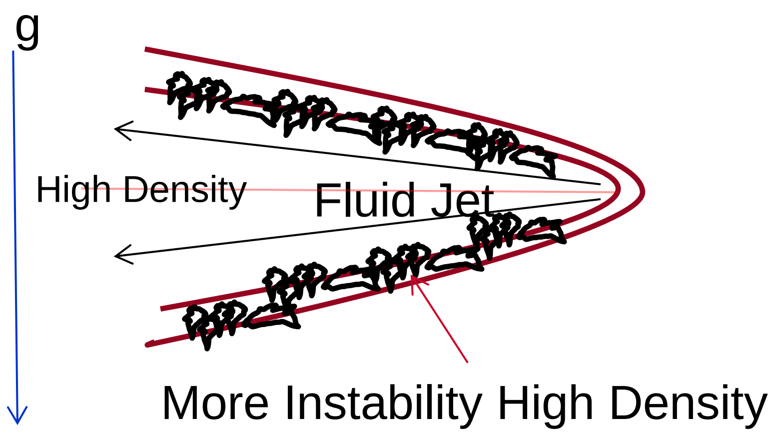
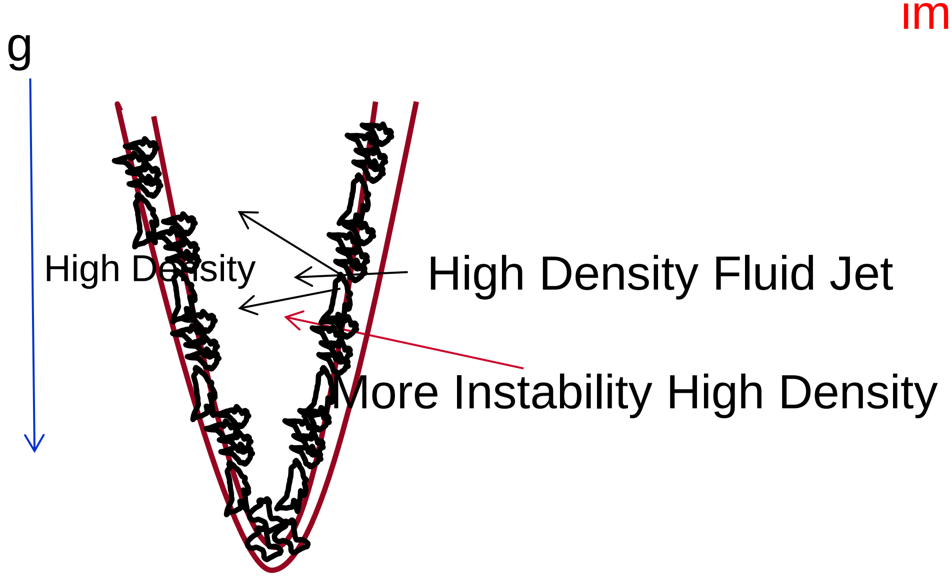
Instability/Cleanup Scenarios in Gravity with Denser Jet: Instability Breeds Asymmetric Cleanup



Rotation of a Pressure Vessel can affect gravity and Instability interfaces

More Unstable region gives better cleanup

Suggests way of performance improvement



Beware of Using A Vertical Well Measurement to Apply to a Horizontal Well

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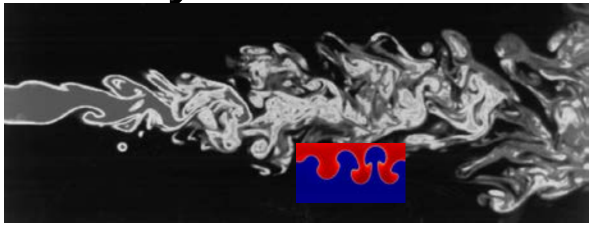
Suggested Section IV Testing

- Flow Test
  - Where does flow come from in perforation tunnel?
  - KH stability?
  - Is it turbulent?
    - Hardened Hot wire anemometer?
    - Visual
- Gravity test
  - Perforation tunnels should be different (asymmetric) depending on direction of gravity. This will be dependent on the difference in density of the interacting fluids
- Charge test
  - Different charges may have different effects
- Roughness tests of perforation tunnels in specific rocks and charges
- Use all this information to optimize cleanup

Discussion: What does this presentation say about Section IV concerning perforations and cleanup?

- Simulation of flow after perforation
  - Shows jet entering along walls of perforation tunnel
  - Shows high Reynolds number (turbulent) flow
- How jet flow cleans up tunnel depends on drag and roughness
  - Drag is enhanced by turbulent flow
  - Roughness affects turbulent drag, but not viscosity
- Interface instabilities may play a role
  - Different cleanup depending on direction of gravity
  - Different cleanup depending on instability interaction

Beware of Using
A Vertical Well Measurement
to Apply to a Horizontal Well



References

- Fluid Mechanics, Landau and Lifshitz
- The Structure of Turbulent Flow, A. A. Townsend
- An Introduction to Fluid Dynamics, G. K. Batchelor
- A First Course in Turbulence, Tennekes and Lumley
- Hydrodynamic and Hydromagnetic Stability, S. Chandrasekhar
- Hydrodynamic Stability, Drazin and Reid
- “The Effect of Surface Roughness on Hydrodynamic Drag and Turbulence”, Thomas A. Shapiro, USNA---Trident Scholar project report; no. 327 (2004)
- “Boundary Layer Drag for Non-smooth Surfaces”, W. W. Gollos, Project Rand Research Memorandum, (1953)

Questions?

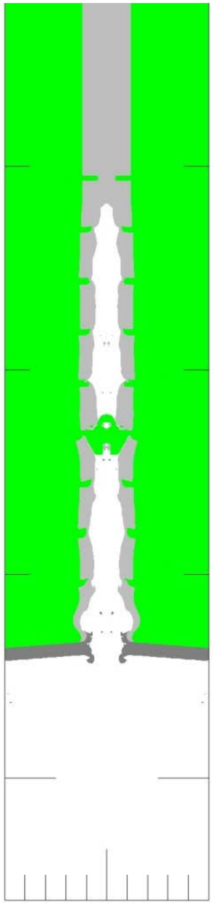
BACKUP

Strategy

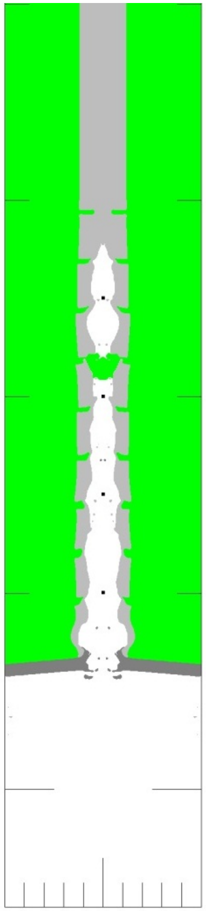
- Use CTH, a hydrodynamic code, to give velocity of pressurized reservoir material (oil and/or gas in rock) into perforation tunnel
- Simulate “QC” setup with sand target pressurized by 5000psi water
- Charge creates cavity then high pressure fluid enters cavity from the sides
- Usual sample 11.2 g charge
- Kelvin-Helmholtz Instability can Drive Turbulence in Jet
- *Drag* is one key to cleanup
  - Drag changes significantly as a function of Reynolds number (R) or fluctuation level
  - Roughness plays a role
- Rayleigh-Taylor Instabilities can be present with Gravity

Effect of Lower water Pressure

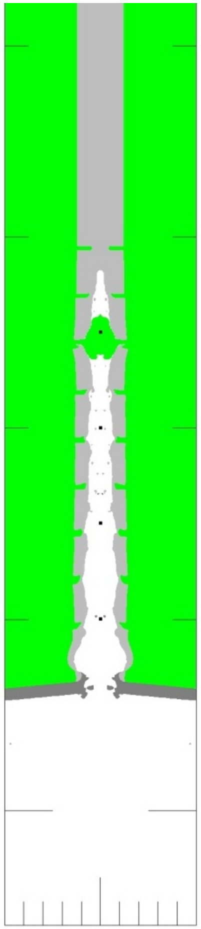
5000psi



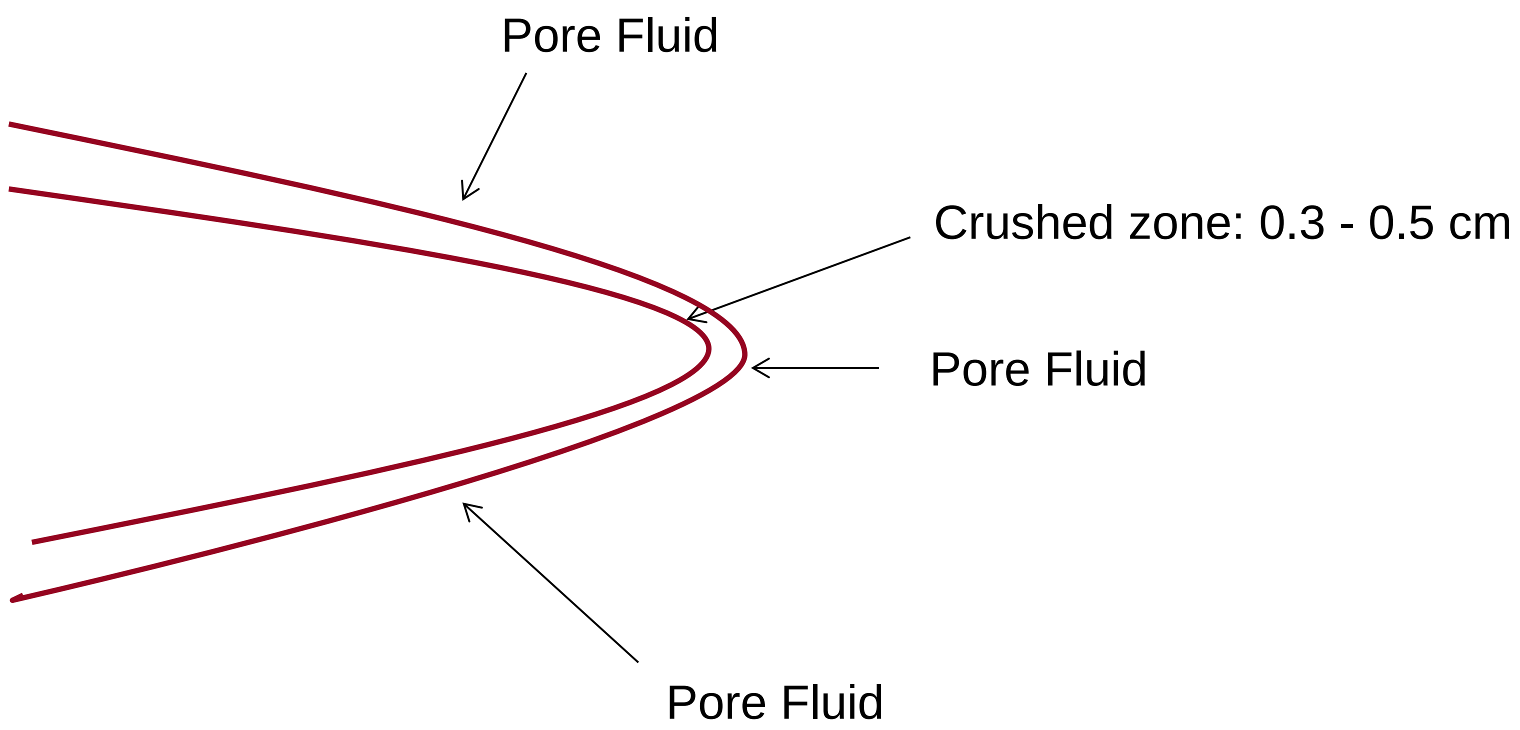
3500psi



2754psi



Perforation Cavity/Tunnel

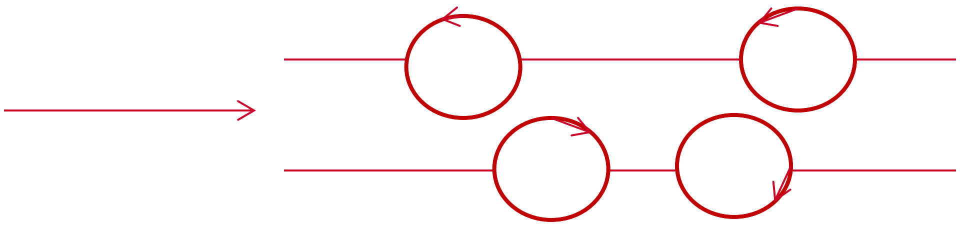


Key to Discussion is Stability: Flow and Density Interfaces are Unstable

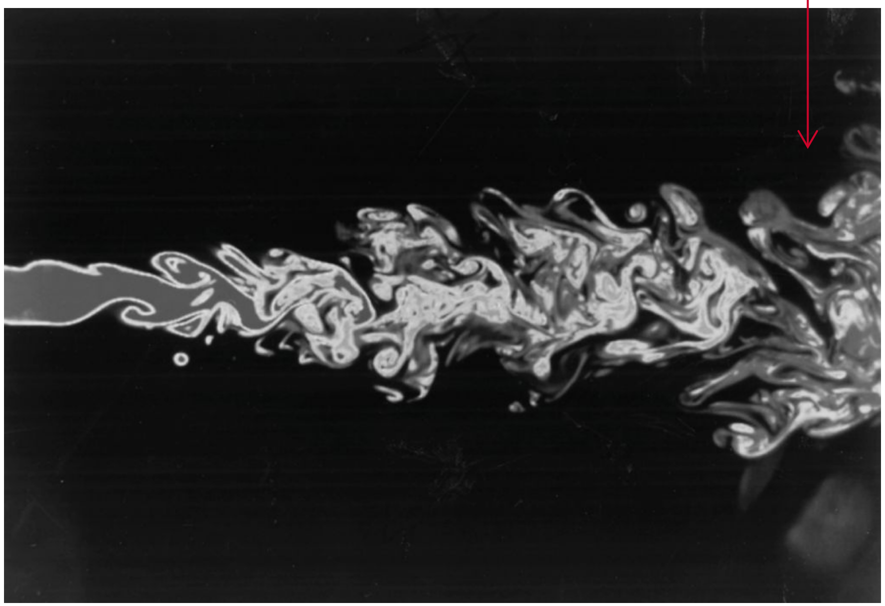
$$\delta \sim \delta_0 \exp(\gamma t)$$

- Instability: Exponential growth of perturbation
- All fluid jets are unstable:
  - – Kelvin-Helmholtz Instability
- Heavy Fluid over light Fluid is unstable in gravity
  - – Rayleigh-Taylor Instability
- One instability can stabilize the other
- Instability leads to turbulence when perturbations overlap

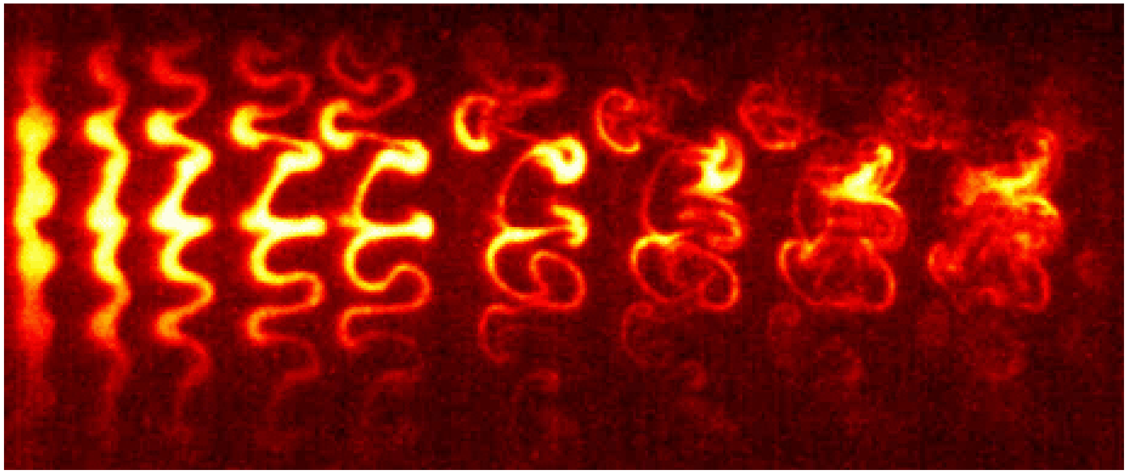
Kelvin-Helmholtz Instability Rolls up Jet



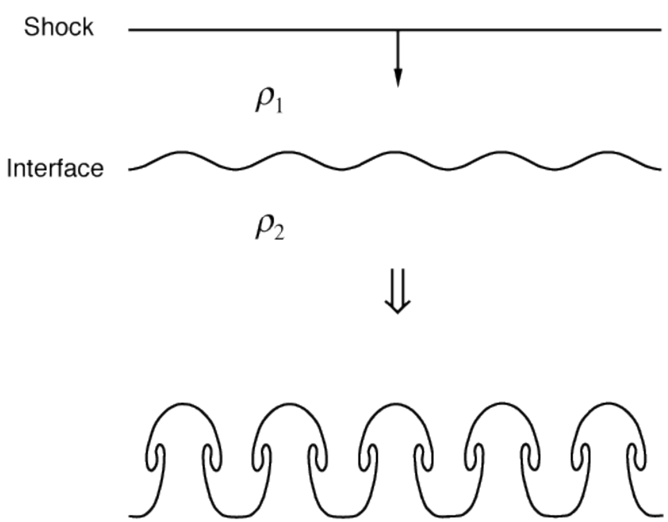
Transition to Turbulence

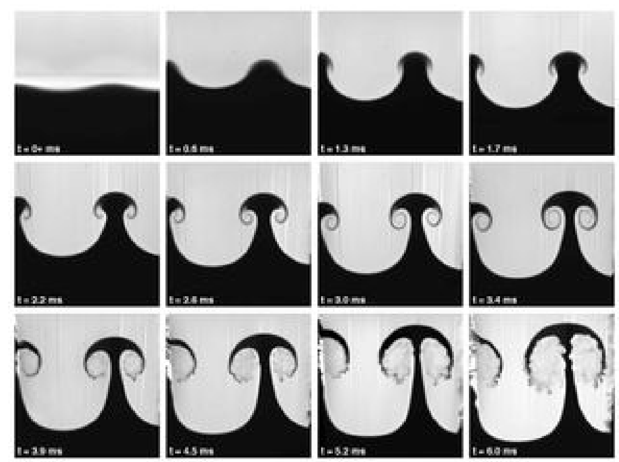


Richtmyer–Meshkov Instability



Grows linearly in time





How will instabilities effect flow in the perforation tunnel?

- Kelvin-Helmholtz (KH) instability is the reason jets are unstable, but Rayleigh-Taylor (RT) instability can stabilize KH
  - KH always present with shear flows
- If the pore fluid is higher or lower density than fluid in perforation, and gravity is not parallel to this interface, then RT instability is present
  - A Jet from tip of tunnel (previous work) will be closer to wall on bottom (or top) of tunnel
    - *Perforation tunnel cleanup would be asymmetric in the direction of gravity*
    - *To make cleanup symmetric*, angle charge a little bit upward (downward)
- For a pore fluid jet not at the tip (along walls), then RT instability would occur for non-vertical holes, but away from jet site and would follow scenario above
- *The Rayleigh-Taylor instability has the potential to play a role in all perforation tunnels*
- Shock induced Rayleigh-Taylor can disrupt pore fluid flow because of shocks elsewhere: Downhole interference in rock

Perforation Tunnels can Interfere with Each Other: Shocks from Nearby Charges can Force Interface Instability due to Richtmyer-Meshkov