2022 NETL Multiphase Flow Science Workshop, August 2-3, 2022

Steady and Pulsating Flow of Cement Slurries

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Challenges in Petroleum Industry

Photo credit: U.S. Coast Guard

Industrial Disaster: Deepwater Horizon explosion
Location: Gulf of Mexico, Louisiana, United States
Data: April 20, 2010
Death: 11
Injuries: 17

"the Chief Council's team is certain that the Macondo cement failed" (Chief Counsel's Report, 2011, pgs 95 – 96)

Problem:

- The offshore oil rig Deepwater Horizon experienced **Gas Migration** after cementing
- Lead to loss of well control and/or blow outs

Tao, C., Rosenbaum, E., Kutchko, B. G., & Massoudi, M. (2021). A brief review of gas migration in oilwell cement slurries. Energies, 14(9), 2369.

Background - Well Cementing

Well Cementing

- Process of placing a cement slurry in the annulus space between the well casing and the surrounding formations
- Primary function is to provide zonal isolation.
- Designed to have a hydrostatic pressure higher than formation pressure and lower than formation fracture pressure

Operation Environment

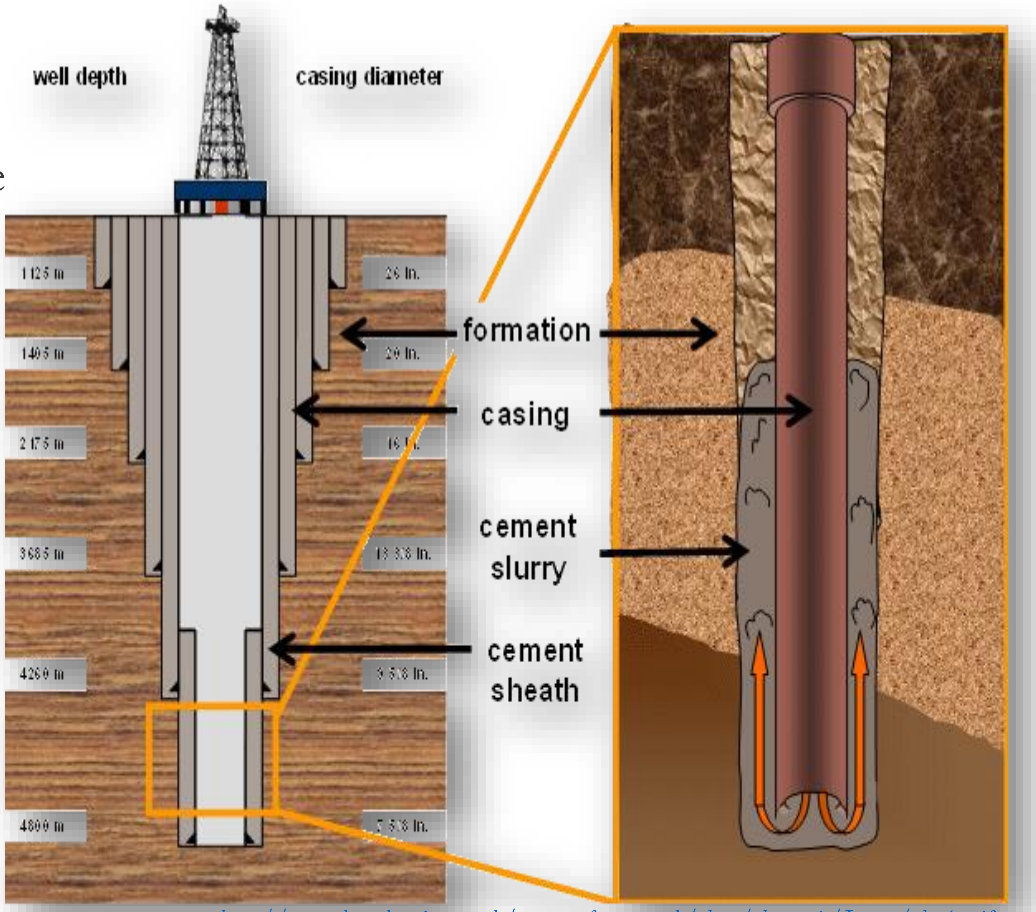
- High temperature & high pressure (*200°C* and *150 MPa* in deep wells)
- Weak or porous formations, corrosive fluids, formation gas

Problems

- Gas migration into wellbore cement
- Permanent pathways can form

Objectives

- Understanding the **rheological properties** of cement in oil well applications
  - **Comprehensive model** for cement slurry
  - **Important parameters** that affect the rheology of cement
- Understanding the process of **gas migration** in the hydrating cement



http://www.bauchemie-tum.de/master-framework/data/dynamic/Image/tbz1e.gif

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Formation Fluids Pressure < **Cement** Hydrostatic Pressure < **Formation** Fracture Pressure

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Well Cement Properties

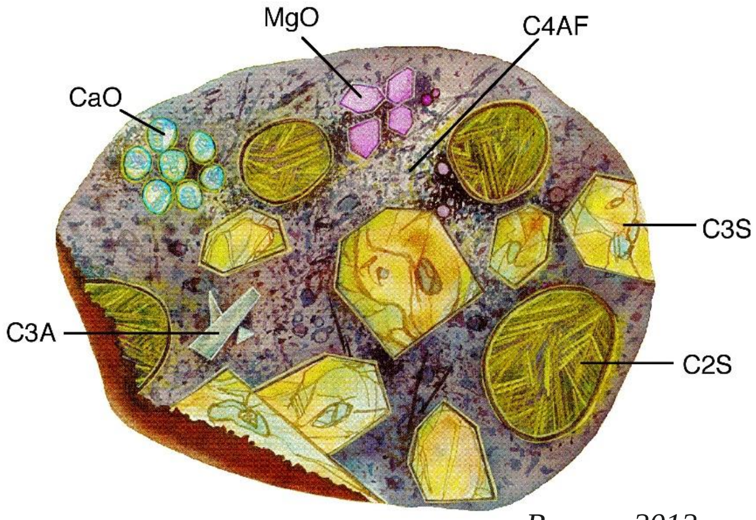
Cement Physical Properties

Cement properties	Value
Cement powder density	3.15 g/cm^3
Cement slurry density	1.442 g/cm^3
Cement particle size	0.1 to 100 μm
Compressive strength	20 - 40 Mpa
Maximum solid concentration	0.65
Reynolds number	2716-3971

Cement Chemical Properties

Mineral phase	Chemical formula	Abbreviation	Percentage
Tricalcium silicate (**Alite**)	Ca_3SiO_5	C_3S	40-70%
Dicalcium silicate (**Belite**)	Ca_2SiO_4	C_2S	15-45%
Tricalcium aluminate (**Aluminate**)	$Ca_3Al_2O_6$	C_3A	1-15%
Tetracalcium aluminoferrite (**Ferrite**)	Ca_2AlO_5, Ca_2FeO_5	C_4AF	0-18%
Magnesium oxide (**Periclase**)	MgO	MgO	2%
Calcium Oxide (**Free lime**)	CaO	CaO	2%

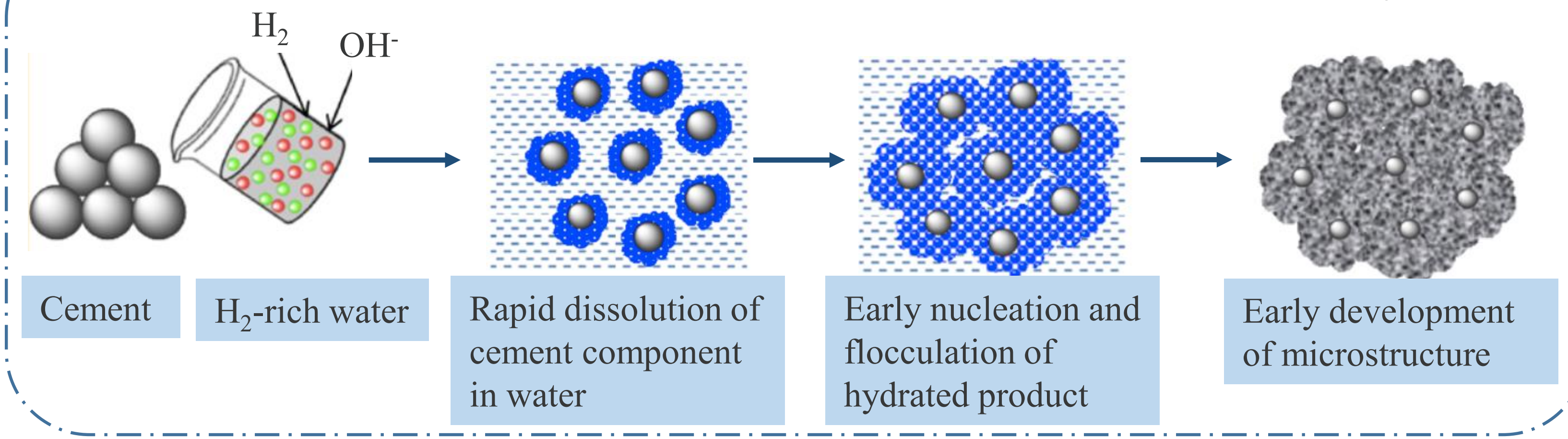
Cross-section of a Cement Particle



Barron, 2012

Cement Hydration Process

Chakraborty et al., 2016

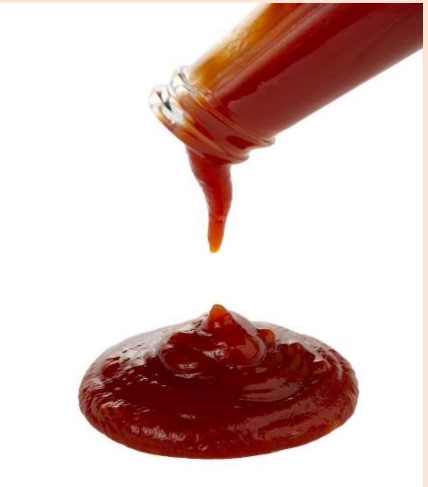


Tao, C., Kutchko, B., Rosenbaum, E, and Massoudi, M. (2020). A Review of Rheological Modeling of Cement Slurry in Oil Well Applications. Energies, 13 (3), 570.

Rheological Behavior of Non-Newtonian Fluids

Shear Thinning (Pseudoplastic)

- Ketchup



- *Viscosity decreases with increasing shear rate*

Shear Thickening (Dilatant)

- Cornstarch and water mixture

- *Viscosity increases with increasing shear rate*

Thixotropic

- Yogurt

- *Viscosity decreases with stress over time*

Rheopectic

- Printer ink

- *Viscosity increases with stress over time*

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Rheological Behavior of Non-Newtonian Fluids

Shear Thinning (Pseudoplastic)	Shear Thickening (Dilatant)	Thixotropic	Rheopectic
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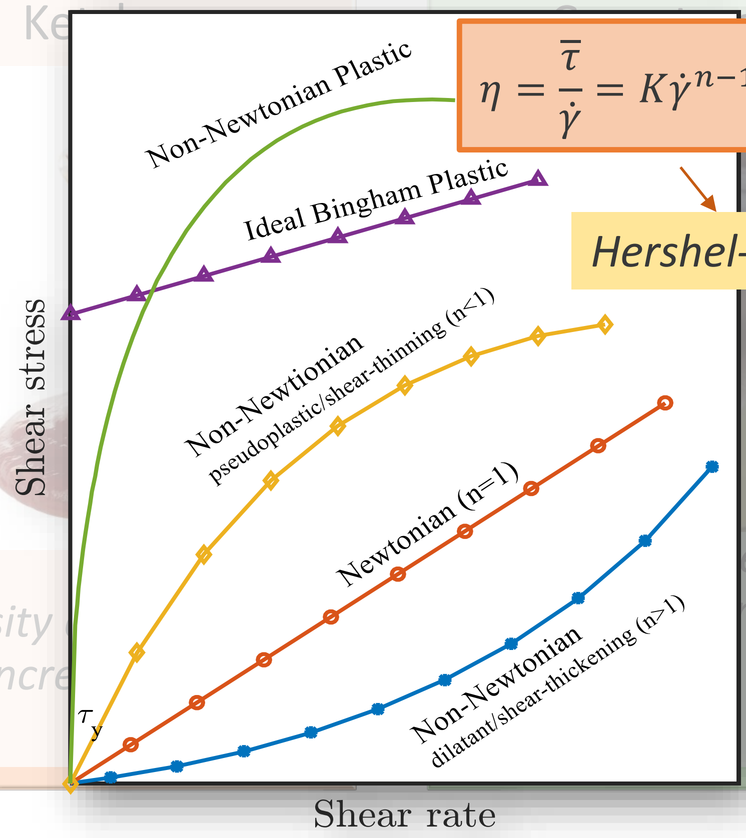
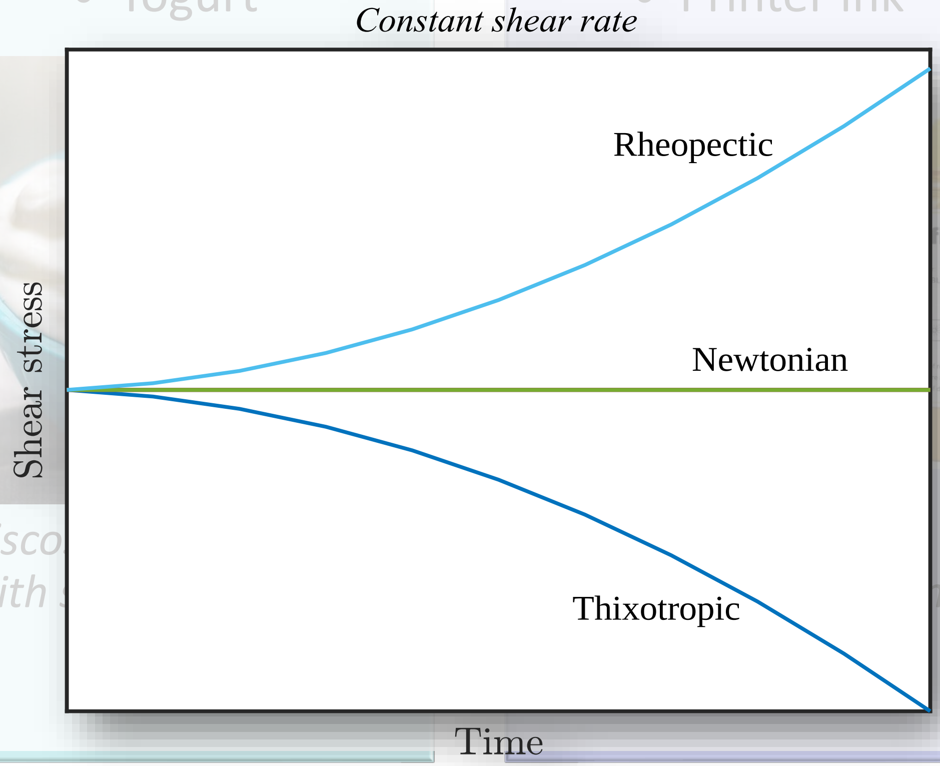


$$\eta = \frac{\overline{\tau}}{\dot{\gamma}} = K\dot{\gamma}^{n-1}$$

1D

Hershel-Bulkley



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Rheology of Cement Slurry

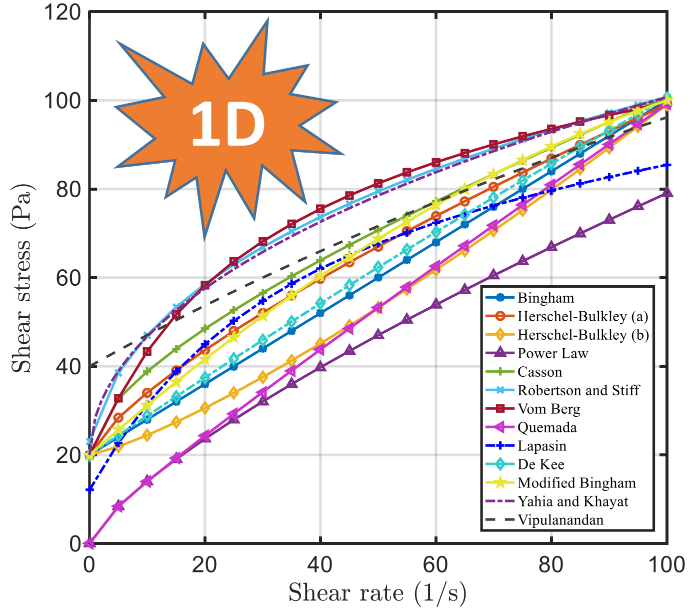
Goals:

- Develop a **comprehensive rheological model** for cement slurry
- Determine **important parameters** that affect rheological behavior

Rheology of cement slurry:

- Viscosity depends on the **shear rate**, **particle concentration**,…
- Cement has a **yield stress**
- Cement shows **thixotropic** behavior

Review of cement constitutive models



In house constitutive model for cement slurry

3D

Total stress:

$$\boldsymbol{T} = \boldsymbol{T}_v + \boldsymbol{T}_y$$

Viscous stress:

$$\boldsymbol{T}_v = -p\boldsymbol{I} + \mu_0\left(1 - \frac{\phi}{\phi_m}\right)^{-\beta}(1+\lambda^n)\left[1+\alpha\operatorname{tr}\boldsymbol{A}_1{}^2\right]^m \boldsymbol{A}_1 + \alpha_1\boldsymbol{A}_2 + \alpha_2\boldsymbol{A}_1{}^2$$

Volume fraction — Thixotropic behavior — Shear rate

Yield stress:

$$\boldsymbol{T}_y = \left[\frac{m_1 \dfrac{\phi^2(\phi-\phi_{perc})}{\phi_m(\phi_m-\phi)} \times (-175w/c + 137)}{\left|\Pi_{\boldsymbol{A}_1}\right|^{1/2}} + K\left|\Pi_{\boldsymbol{A}_1}\right|^{\frac{n-1}{2}}\right]\boldsymbol{A}_1 \quad \text{for } \Pi_{\boldsymbol{A}_1}^{1/2} > \dot{\gamma}_c$$

Volume fraction — Water to cement ratio — Shear rate

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Mathematical Model-Governing Equations

- **Conservation of mass**

$$\frac{\partial \rho}{\partial t} + div(\rho \boldsymbol{v}) = 0$$

ρ: density of cement slurry

$\boldsymbol{v}$: velocity vector, $div(\boldsymbol{v}) = 0$ for an isochoric motion

- **Conservation of linear momentum**

$$\rho \frac{d\boldsymbol{v}}{dt} = div\boldsymbol{T} + \rho \boldsymbol{b}$$

d/dt: total time derivative, given by $\frac{d(.)}{dt} = \frac{\partial (.)}{\partial t} + [grad(.)]\boldsymbol{v}$

$\boldsymbol{b}$: body force vector

$\boldsymbol{T}$: Cauchy stress tensor given by the constitutive equation

- **Conservation of angular momentum**

$$\boldsymbol{T} = \boldsymbol{T}^T$$

- **Convection - diffusion equation**

$$\frac{\partial \phi}{\partial t} + div(\phi \boldsymbol{v}) = \mathrm{f}$$

ϕ: volume fraction

f: diffusive particle flux

Constitutive Relations

$$\boldsymbol{T}_v = -p\boldsymbol{I} + \mu_{eff}(\boldsymbol{\phi}, \boldsymbol{A}_1)\boldsymbol{A}_1 + \alpha_1 \boldsymbol{A}_2 + \alpha_2 \boldsymbol{A}_1{}^2$$

$$\mathrm{f} = -\mathrm{div}\boldsymbol{N}$$

$$\boldsymbol{N} = \boldsymbol{N}_c + \boldsymbol{N}_\mu + \boldsymbol{N}_b = -a^2 \phi K_c \nabla(\dot{\gamma}\phi) - a^2 \phi^2 \dot{\gamma} K_\mu \nabla(\ln \mu_{eff}) - D\nabla\phi$$

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Mathematical Model-Constitutive Relations

I. For the viscous stress tensor T

$$\boldsymbol{T} = \boldsymbol{T}_y + \boldsymbol{T}_v$$

$\boldsymbol{T}_y$: yield stress – future work

$\boldsymbol{T}_v$: viscous stress, which is dependent on shear rate, particle volume fraction, temperature, pressure, cement hydration, etc.

A modified second grade (Rivlin-Ericksen) fluid model is applied for viscous stress of cement slurry (Massoudi & Tran, 2016)

$$\boldsymbol{T}_v = -p\boldsymbol{I} + \mu_{eff}(\phi, \boldsymbol{A_1})\boldsymbol{A_1} + \alpha_1\boldsymbol{A_2} + \alpha_2\boldsymbol{A_1}^{\boldsymbol{2}} \qquad (5)$$

p: pressure

ϕ: volume fraction

$\boldsymbol{A_n}$: n-th order Rivlin-Ericksen tensors

where $\boldsymbol{A_1} = \nabla\boldsymbol{v} + \nabla\boldsymbol{v}^T \quad \boldsymbol{A_2} = \frac{d\boldsymbol{A_1}}{dt} + \boldsymbol{A_1}\nabla\boldsymbol{v} + \nabla\boldsymbol{v}^T\boldsymbol{A_1}$

α_1, α_2: normal stress coefficients

μ_{eff}: effective viscosity, which is dependent on volume fraction (Krieger 1959) and shear rate

$$\mu_{eff}(\phi, \boldsymbol{A_1}) = \mu_0\left(1 - \frac{\phi}{\phi_m}\right)^{-\beta}\left[1 + \alpha\mathrm{tr}\boldsymbol{A_1}^2\right]^m$$

μ_0: viscosity of the cement slurry without particles; ϕ_m: maximum volume concentration of solids; β, m: material parameters

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Mathematical Model - Constitutive Relations

II. For the diffusive particle flux f

$$\mathrm{f} = -\mathrm{div}\boldsymbol{N} \qquad (6)$$

$\boldsymbol{N}$: flux vector, related to the movement of the particles (Philips et al, 1992)

$$\boldsymbol{N} = \boldsymbol{N_c} + \boldsymbol{N_\mu} + \boldsymbol{N_b} = -a^2\phi K_c \nabla(\dot{\gamma}\phi) - a^2\phi^2\dot{\gamma}K_\mu \nabla(\ln\mu_{eff}) - D\nabla\phi$$

particles collision **spatially varying viscosity** **Brownian diffusive flux**

D is the diffusion coefficient (diffusivity), which is the function of $\dot{\gamma}$ and ϕ

$$D(\dot{\gamma},\phi) = \eta\left\|\boldsymbol{A_1}^2\right\| \cdot D_0[K_1 + K_2(1-\phi)^2 + K_3(\phi_m - \phi)^2 H(\phi_m - \phi)]$$

(Bridges and Rajagopal 2006; Garboczi and Bentz 1992)

a: particle radus; K_c and K_μ: empirically coefficients; D_0: the diffusivity parameter

K_1,K_2 and K_3: fitting coefficients,H: Heaviside function, $H(x) = 1$ for $x > 0$, $H(x) = 0$ for $x \leq 0$

Substitute two constitutive relations (5) (6) into convection-diffusion equation (4)

Cement Slurry Model

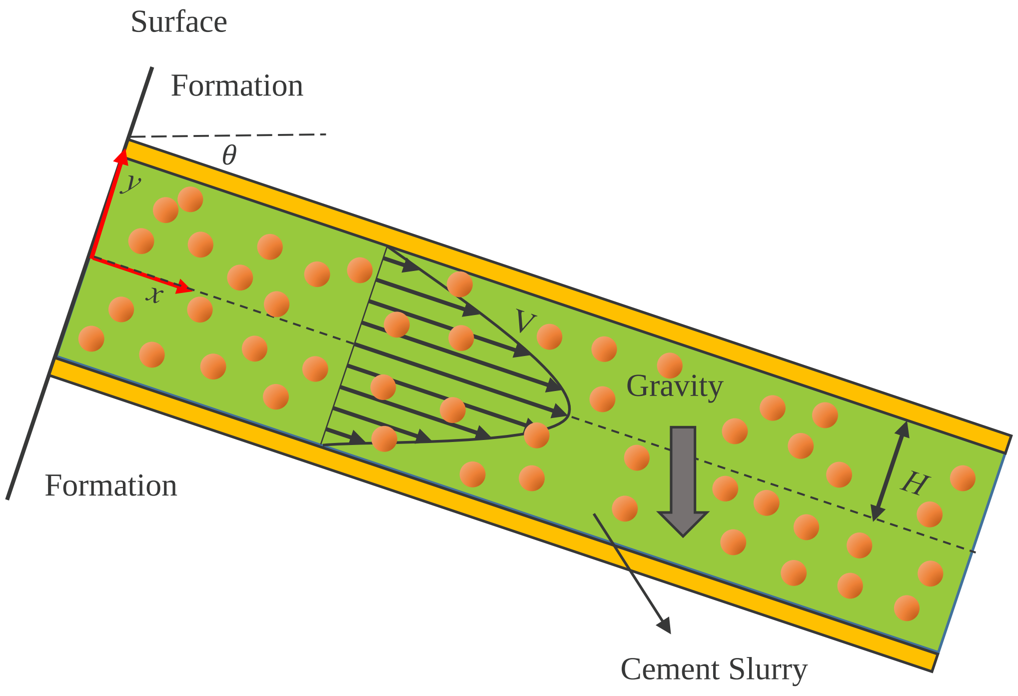
Example 1: Steady Flow of a Cement Slurry

MODEL DESIGN

- Constitutive cement model – cement flow at offshore wellbore conditions
- Cement slurry modeled as non-Newtonian fluid
- Viscosity depends on the shear rate and particle concentration
- Study the impact of parameters on behavior of cement slurry

OUTCOMES

- Parametric study results indicate that the following significantly affect the **velocity** and **volume fraction**:
  - Angle of inclination θ
  - Maximum packing fraction of cement particles
  - Pressure and gravity terms



Schematic diagram of cement slurry flow in an inclined channel

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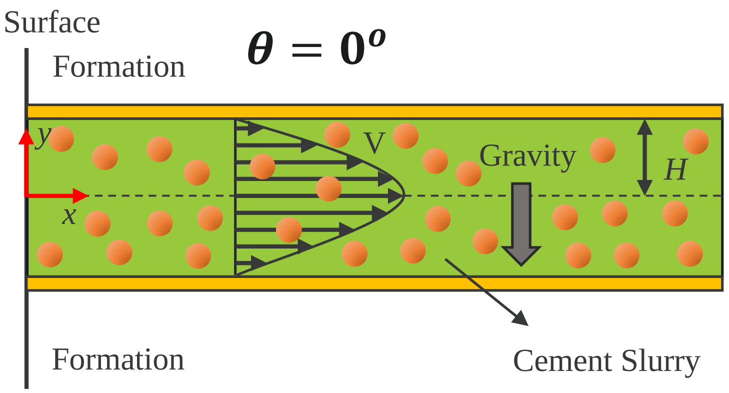
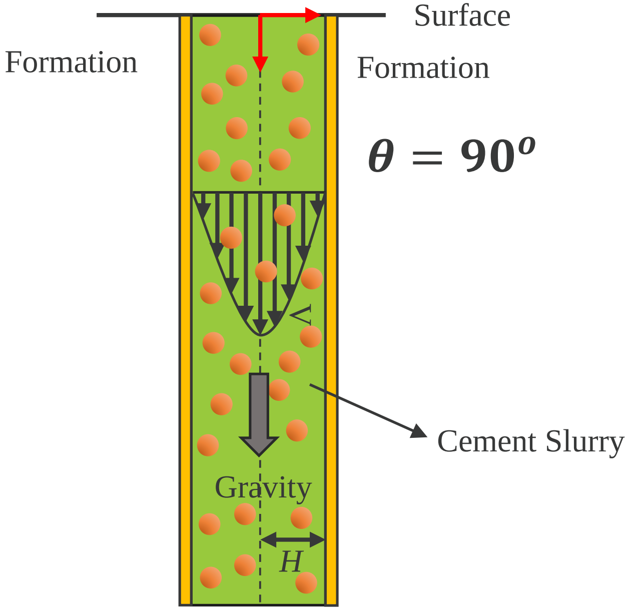
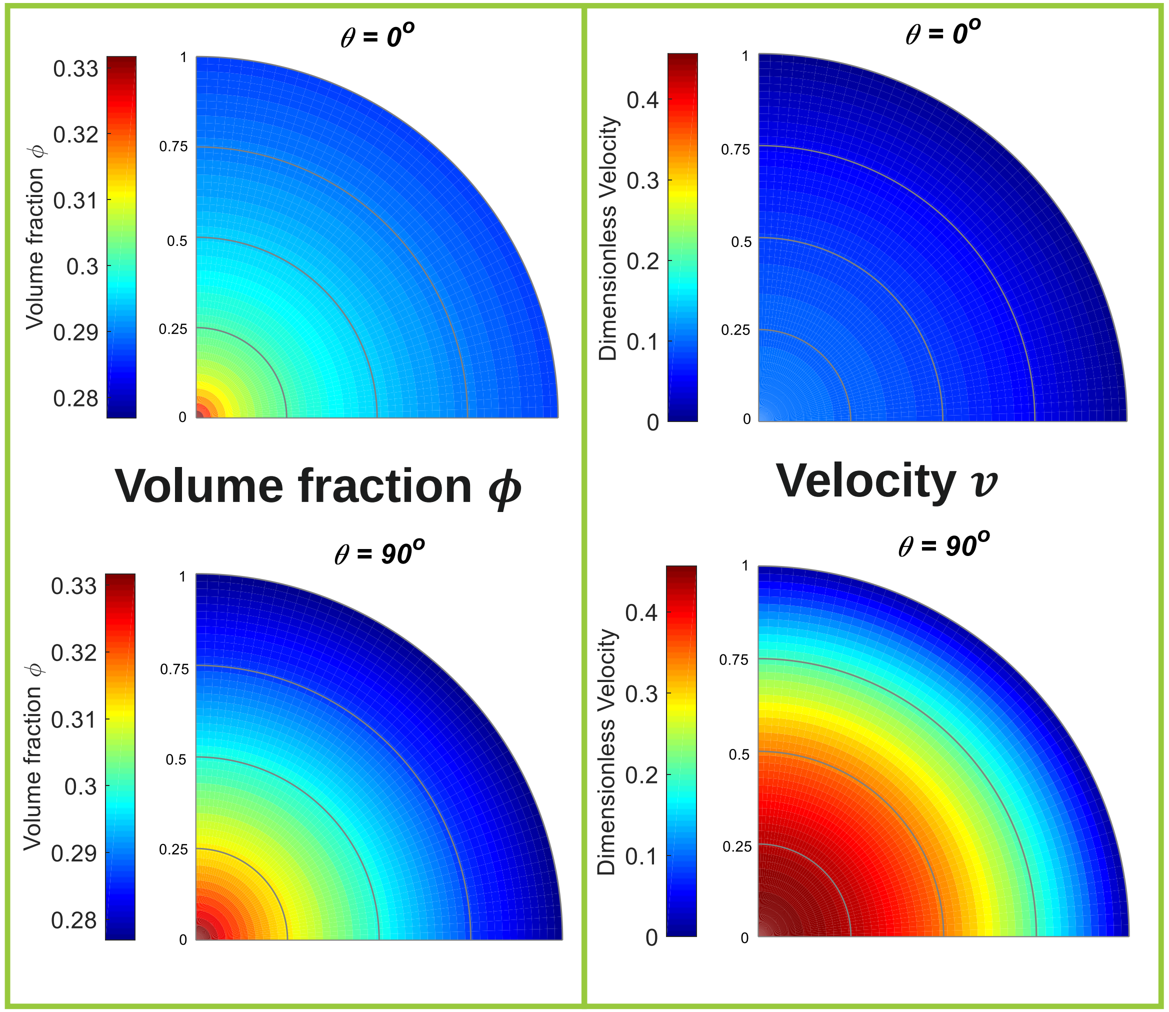
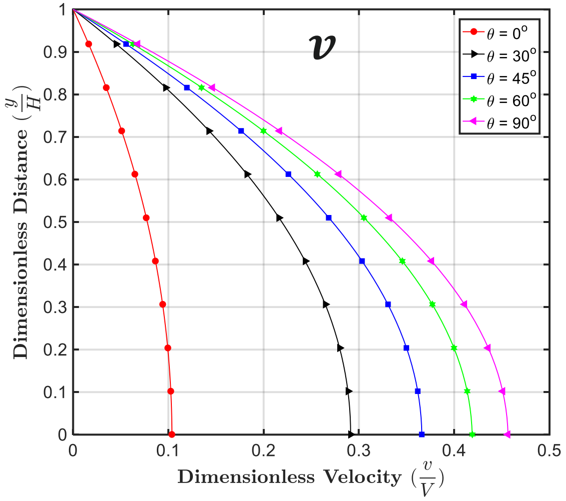
Parametric Study

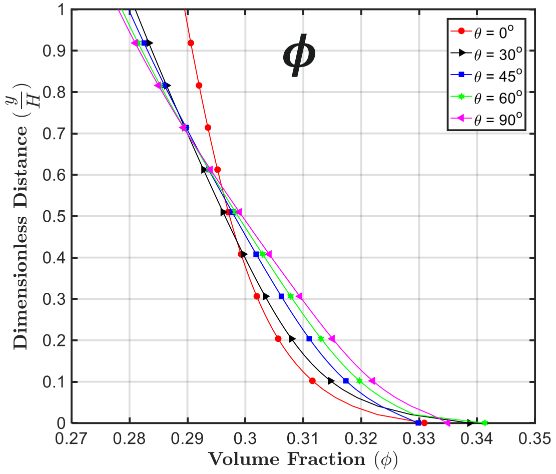
Effect of Inclination Angle, θ











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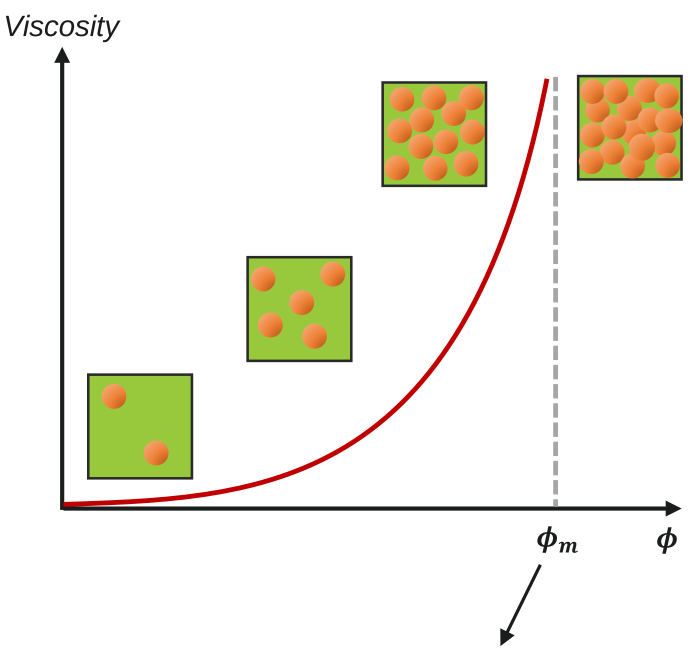
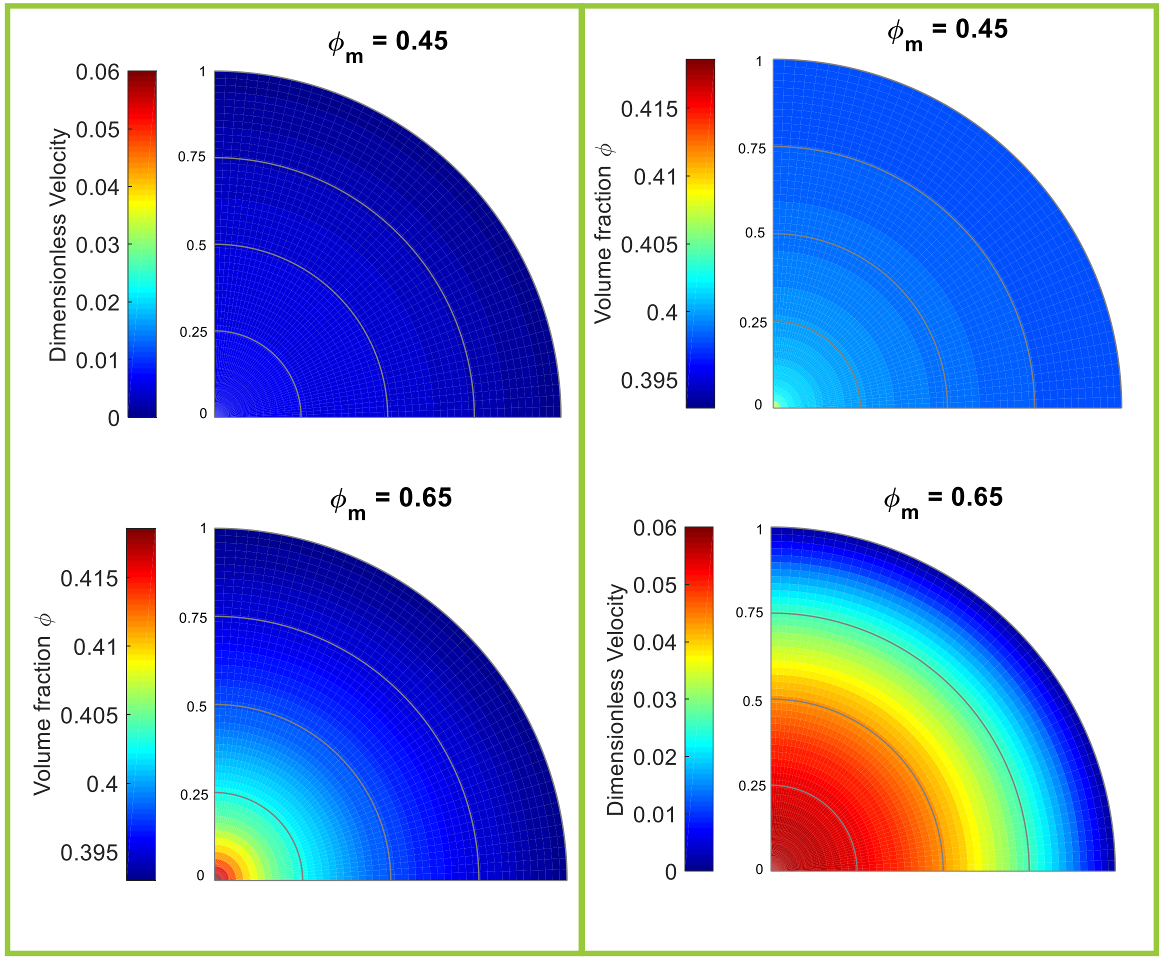
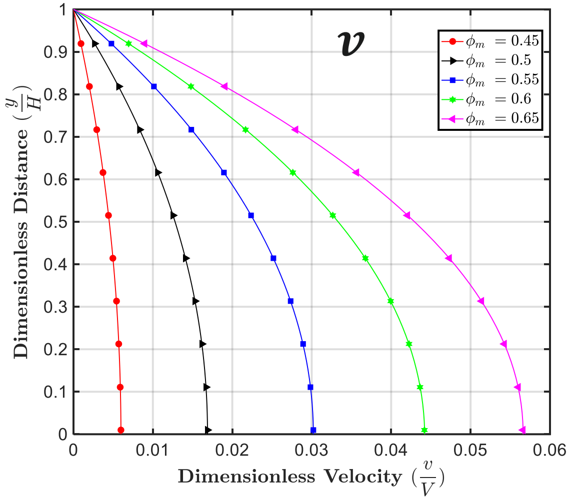
Parametric Study

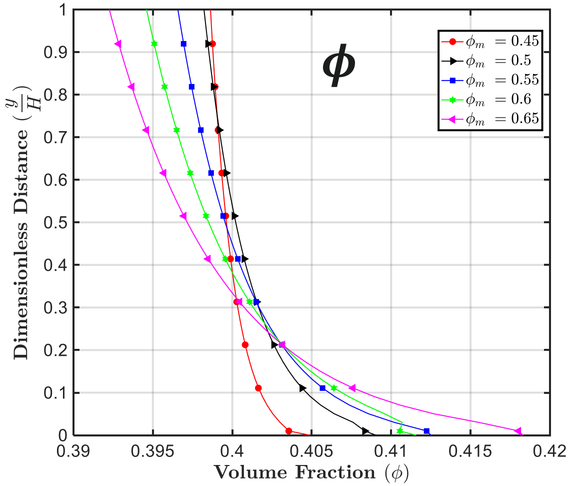
Effect of maximum packing fraction ϕ_m



Maximum packing fraction ϕ_m:
Volume fraction of aggregates in closest-packing at which the relative viscosity approaches infinity.

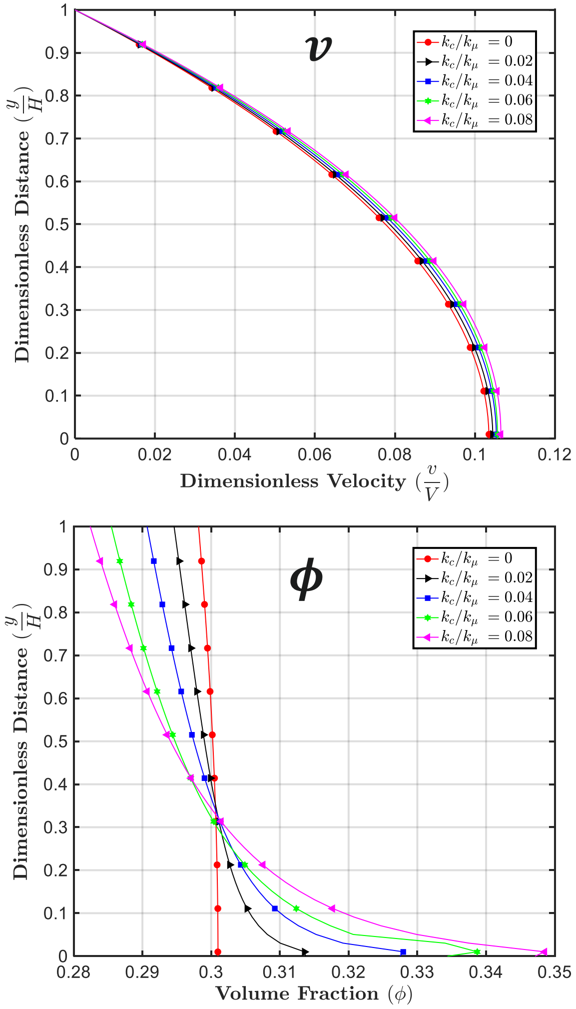




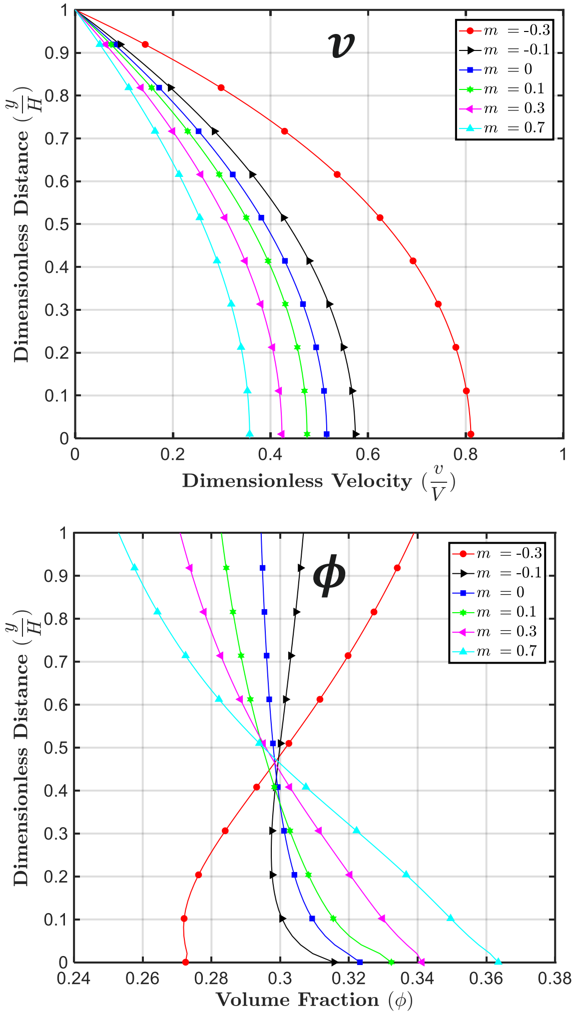


Parametric Study

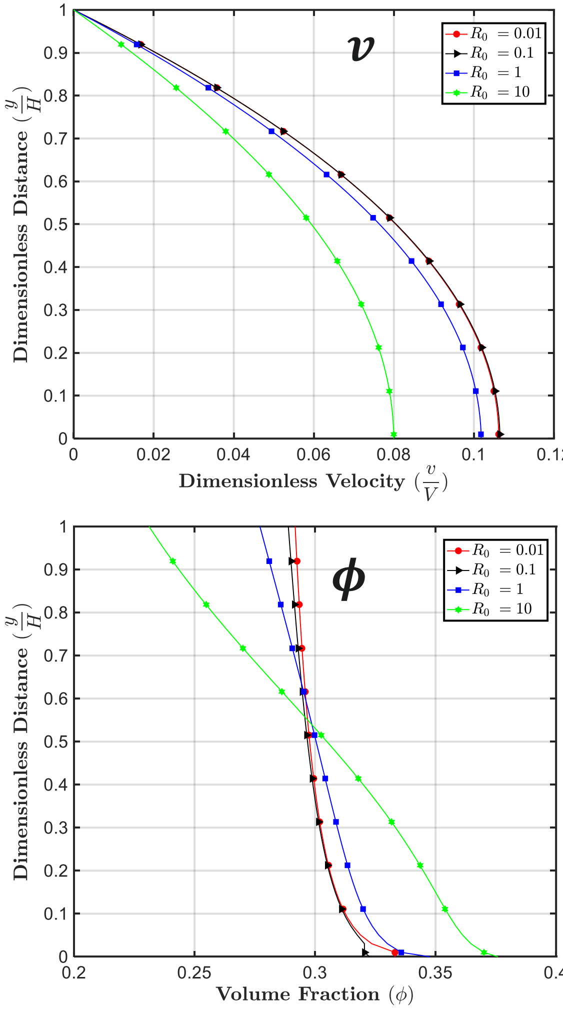
Effect of K_c/K_μ



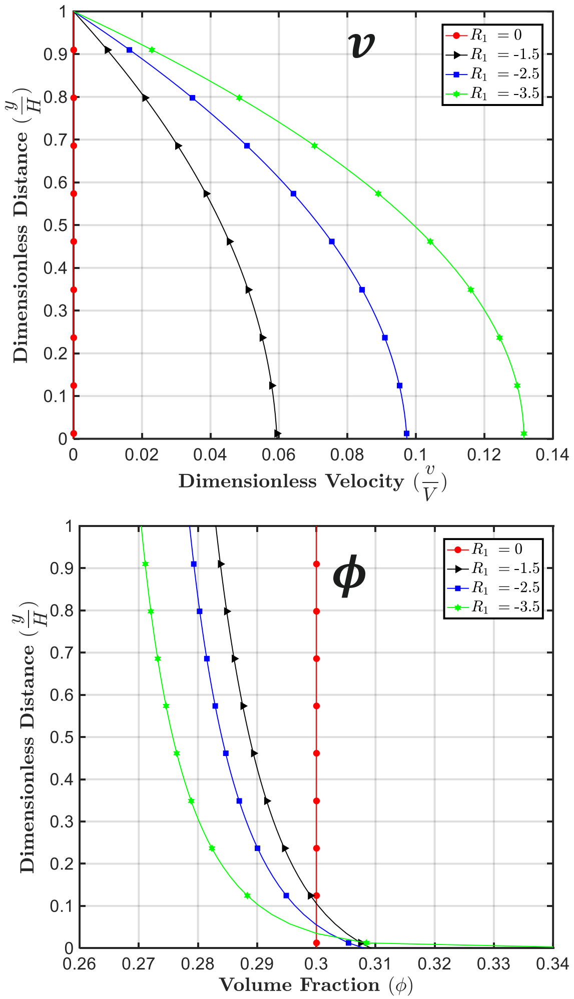
Effect of m



Effect of R_0



Effect of R_1



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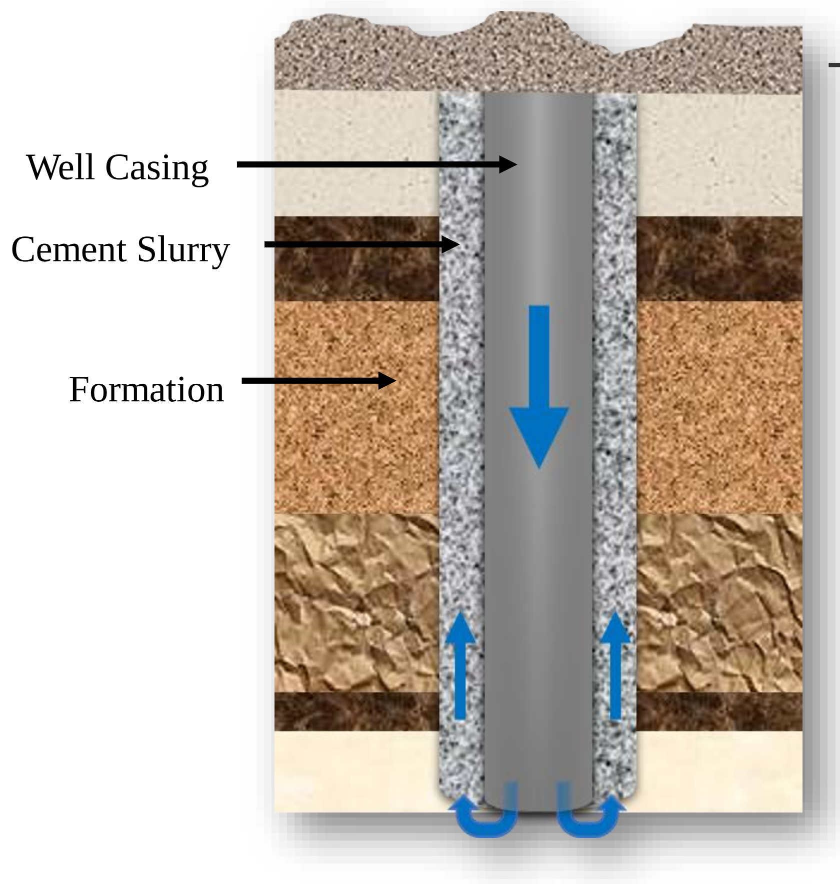
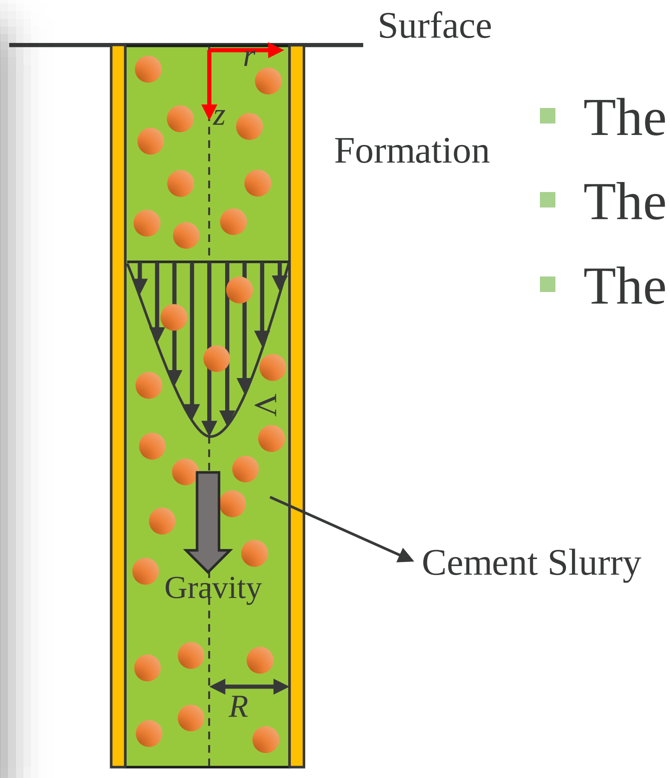
Cement Slurry Model

Example 2: Pulsating Poiseuille Flow of a Cement Slurry





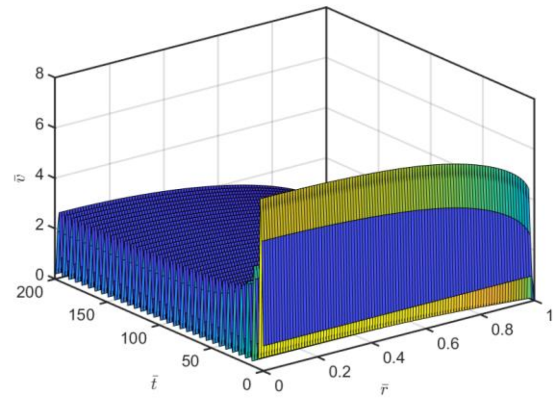
- The motion is unsteady and in transient state
- The flow is assumed to be one-dimensional
- The velocity and the volume fraction forms:

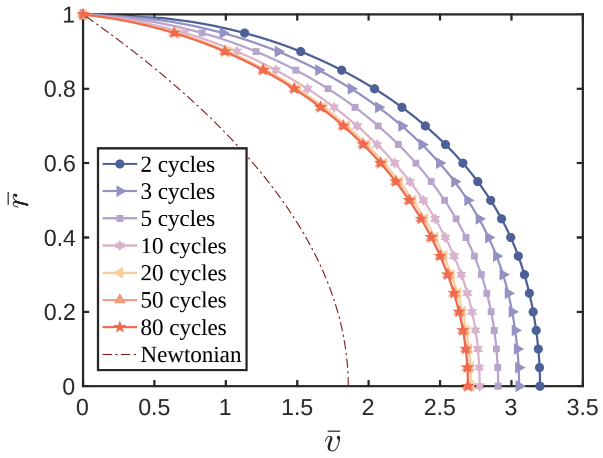
$$\begin{cases} \phi = \phi(\mathrm{r}, t) \\ \boldsymbol{v} = v(r, t)\boldsymbol{e_z} \end{cases}$$

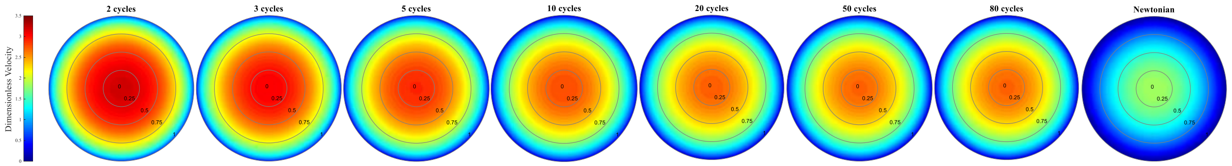
Tao, C., Rosenbaum, E., Kutchko, B., & Massoudi, M. (2021). Pulsating Poiseuille flow of a cement slurry. International Journal of Non-Linear Mechanics, 133, 103717.

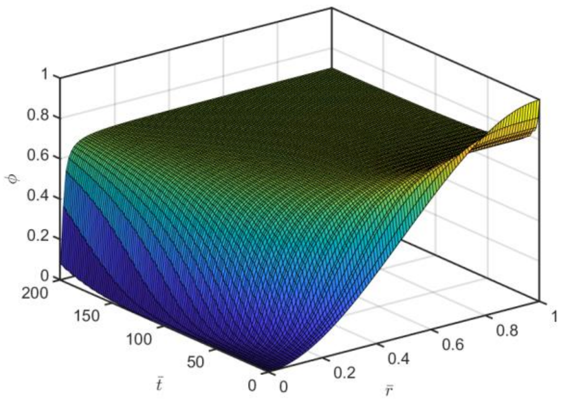
Parametric Study

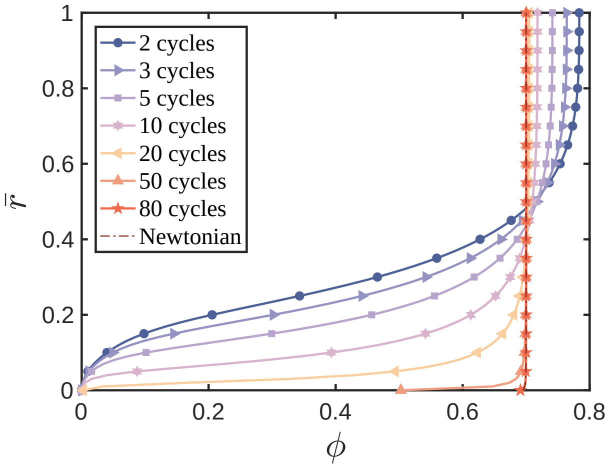
Effect of time cycles

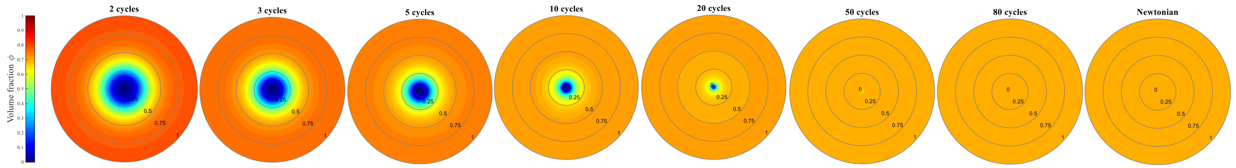












Distribution of velocity & volume fraction at different time cycles in the pipe

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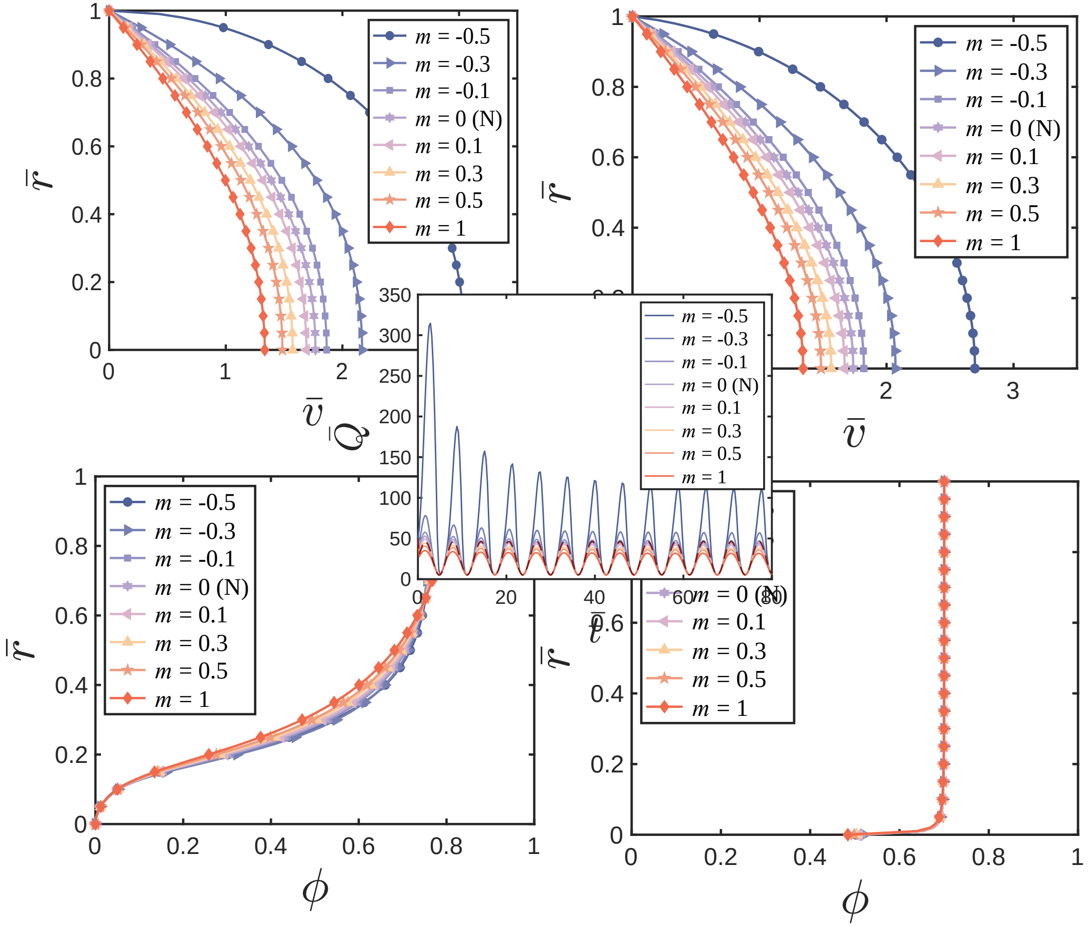
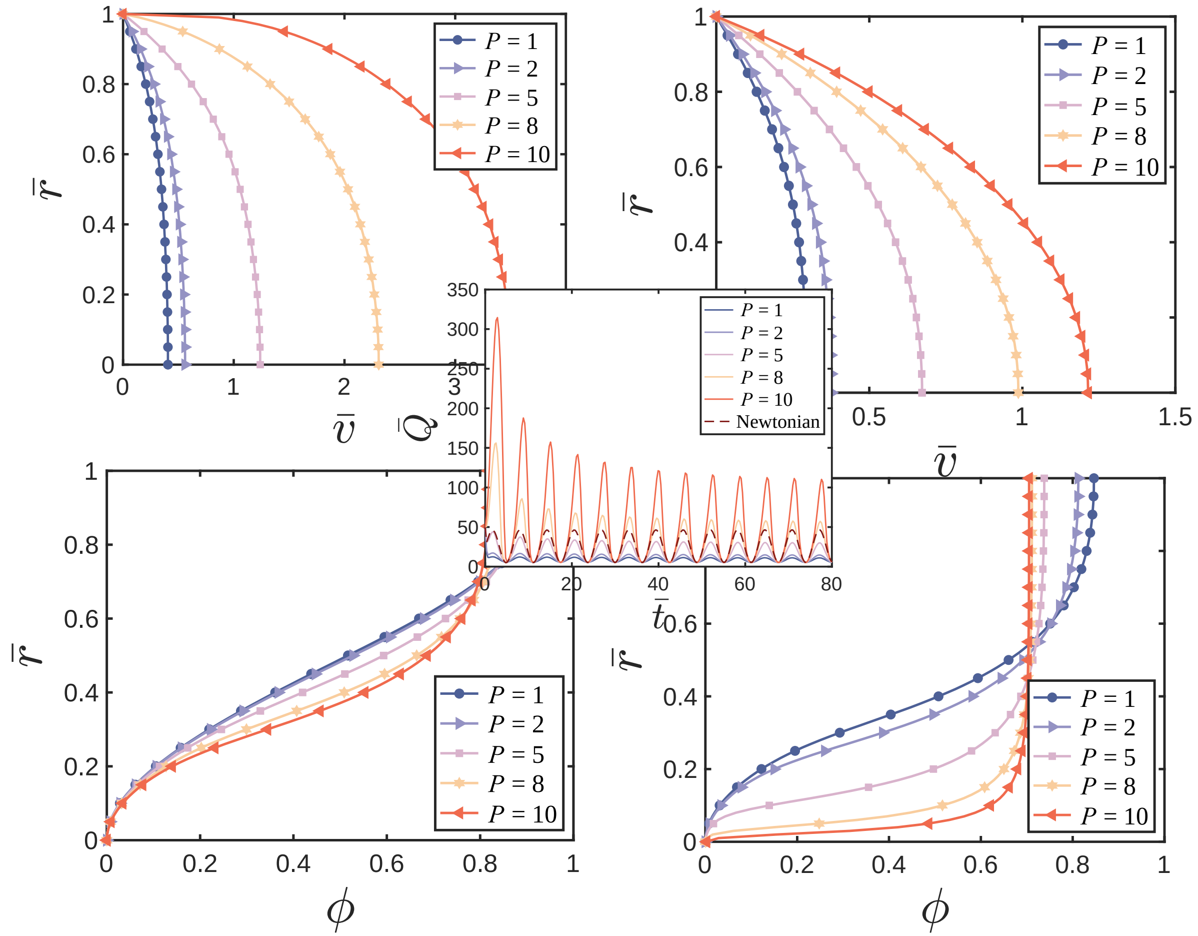
Parametric Study

Effect of m

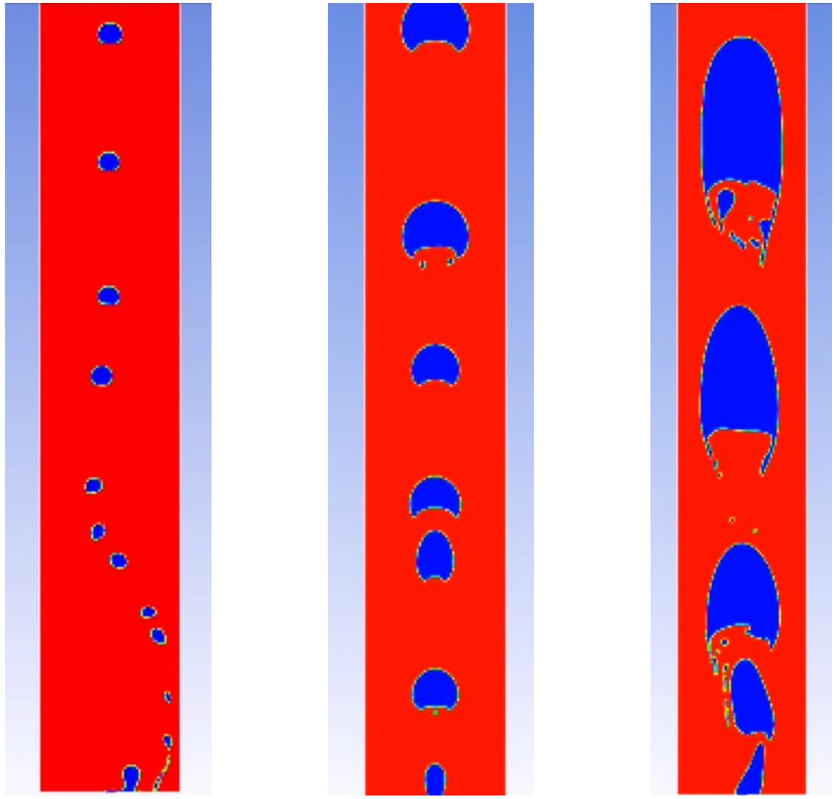


Effect of Pressure



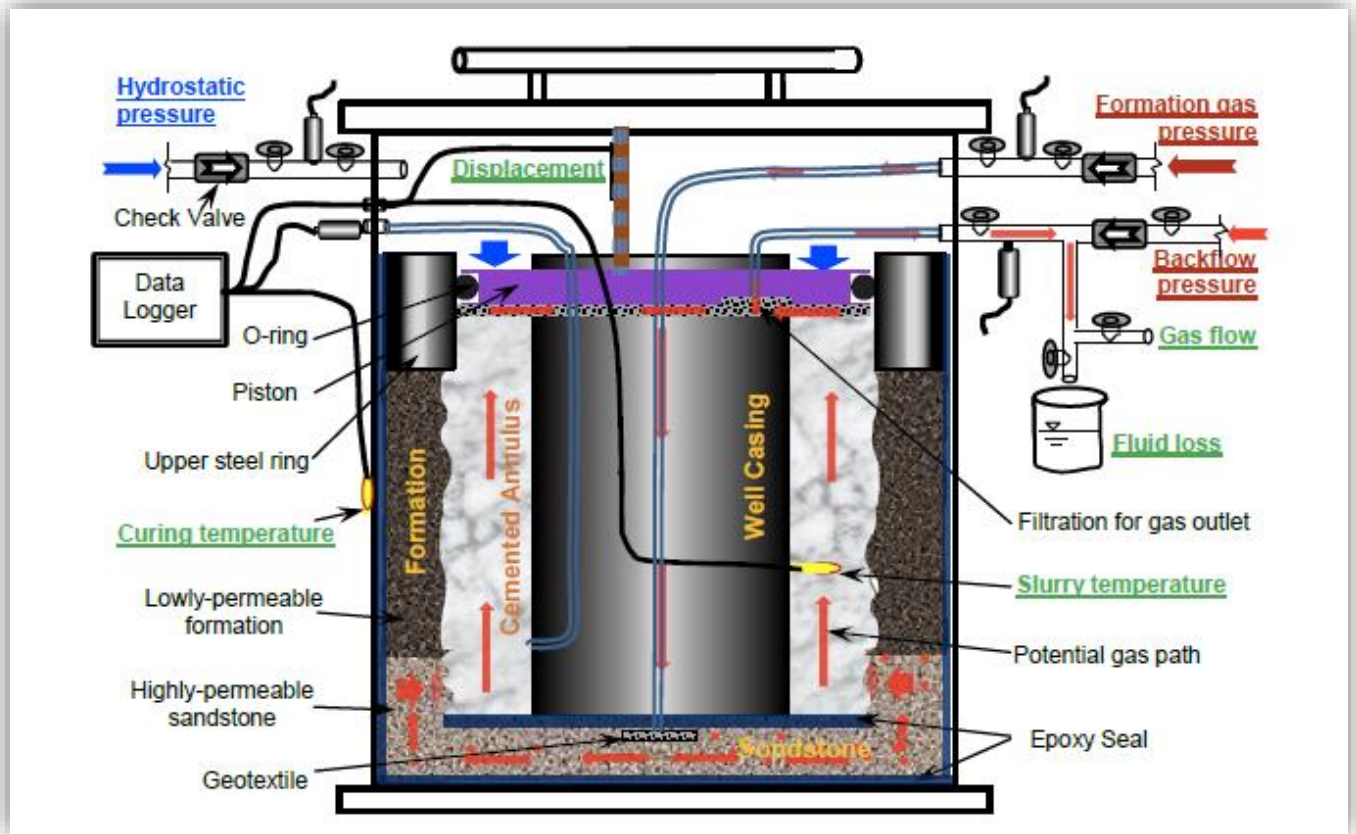
Simulations & Experiments

Channel Flow Air in Fluid Simulations



V = 0.01 (m/s) V = 0.2 (m/s) V = 1 (m/s)

Wellbore Simulation Chamber



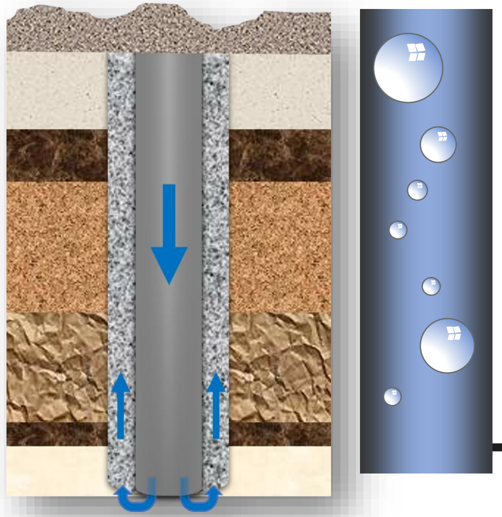
- Max 1500 psi (~depth 1850 ft)
- 20^{o}C to 60^{o}C

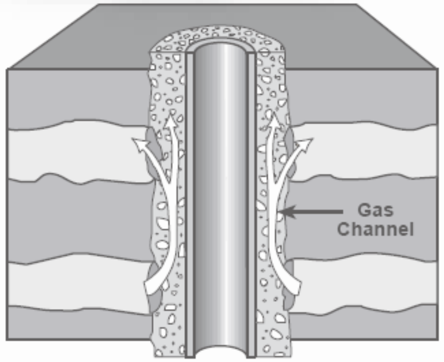
@ University of Pittsburgh

Mofakham, A., Ahmadi, G., Tao, C., Massoudi, M., Rosenbaum, E., Kutchko, B., Computational Modeling of Oil Well Cementing and Gas Migration Process, *Proceeding of the ASME 2020 Fluids Engineering Division Summer Meeting*, FEDSM2020, July 12-16.

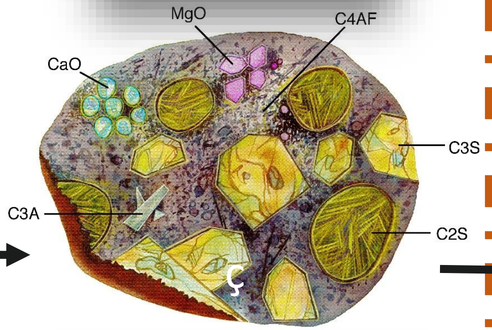
Conclusions

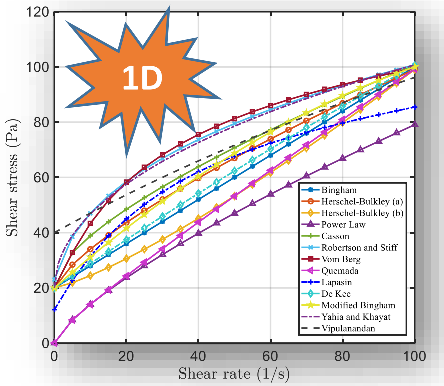
Gas Migration in Well Cementing





Cement Rheology





Comprehensive Constitutive Model for Cement Slurry

Viscous stress:

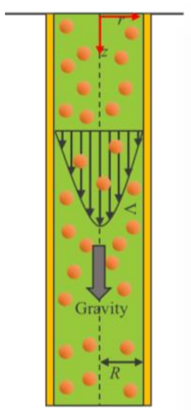
$$\boldsymbol{T}_v = -p\boldsymbol{I} + \mu_0\left(1-\frac{\phi}{\phi_m}\right)^{-\beta}(1+\lambda^n)\left[1+\alpha \mathrm{tr}\boldsymbol{A}_1{}^2\right]^m \boldsymbol{A}_1 + \alpha_1\boldsymbol{A}_2 + \alpha_2\boldsymbol{A}_1{}^2$$

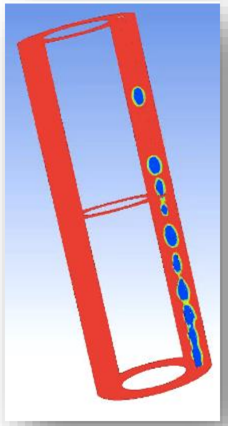
Yield stress:

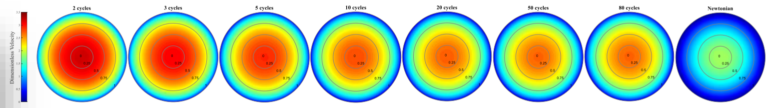
$$\boldsymbol{T}_y = \left[\frac{m_1 \dfrac{\phi^2(\phi-\phi_{perc})}{\phi_m(\phi_m-\phi)} \times (-175w/c+137)}{\left|\Pi_{A_1}\right|^{1/2}} + K\left|\Pi_{A_1}\right|^{\frac{n-1}{2}}\right]\boldsymbol{A}_1$$

3D

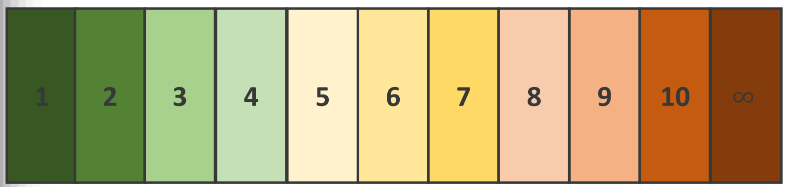
Parametric Study with CFD







Gas flow potential factor



Flow condition 1 Minor | Flow condition 2 Moderate | Flow condition 3 Severe

Mitigate the Geotechnical Infrastructure Hazard

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