Numerical Simulation of Oil Well Cementing and Gas Migration Process

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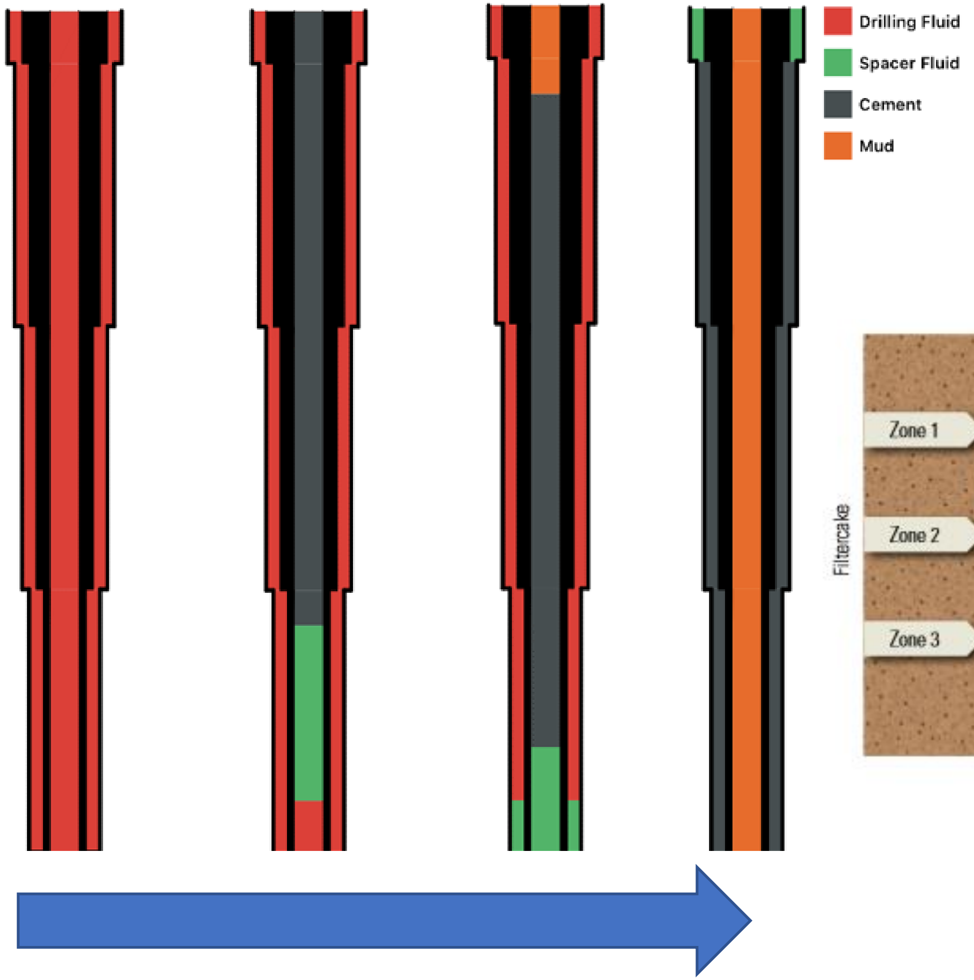
Outline

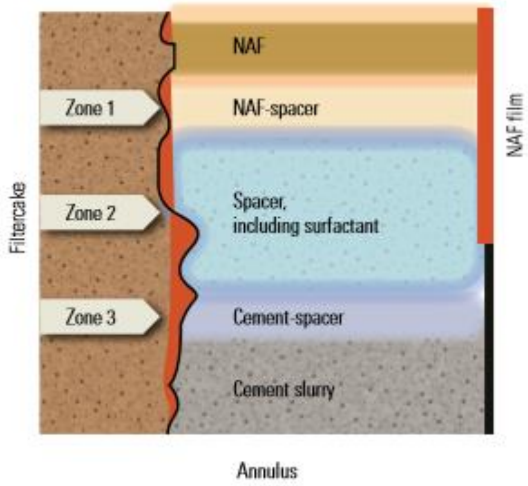
- Introduction
- Cementing Process
- Gas Migration
- Objectives
- Results
- Conclusions

Introduction

Well Cementing Process

- Inject drilling fluid
- Inject spacer fluid
  - Compatible with the drilling fluid/cement slurry
  - Change surface wettability
  - Remove debris
- Inject cement slurry
- Inject mud





Parameters Affecting Well Cement

- Casing equipment (collars, centralizers, well cleaners)
- Spacer fluid
- Pipe surface finishing (roughness)
  - Mill varnish, Sandblasted, Rusty, Resin-sand coated
- Thermal and stimulation stresses
  - Hydration heat
  - Completion, stimulation, production pressure

Gas Migration

- During the cementing process, cement experiences three distinct phases (Slurry, Gel, and Solid).
- In the slurry phase, the cement begins to hydrate, pore pressure begins to drop, and gas migration could begin to occur due to the higher formation pressure.
- In the solid phase, the cement becomes impermeable and no fluid can invade through
- The gel phase is most critical during which formation gas could migrate into the cement if the pore pressure is lower than the formation pressure.

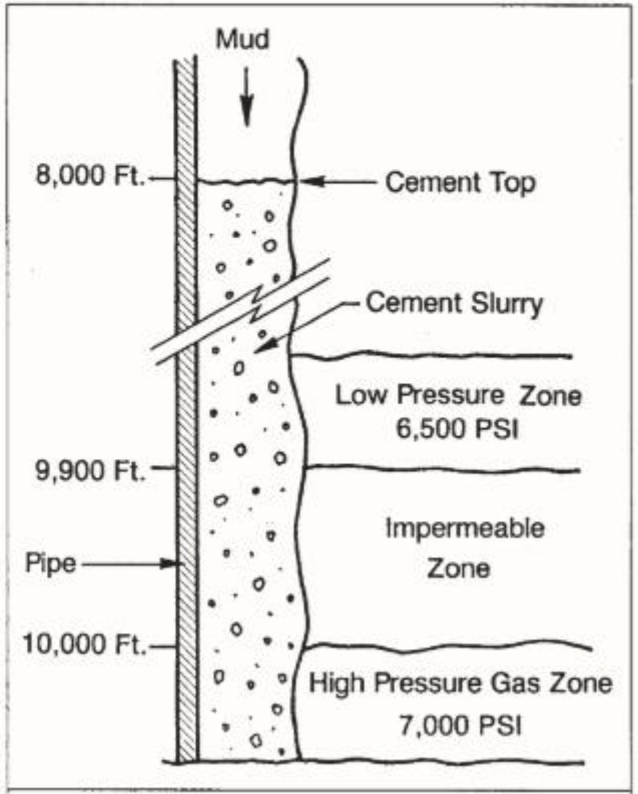


Fig. 2—Imaginary well conditions.

Beirut and Cheung, SPE Production Engineering, 1990

Industrial Practices to Prevent Gas Migration

- Properly clean the wellbore
- Use proper fluid spacers
- Use additives to
  - Control fluid loss
  - Control the setting time
  - Reduce the transition time
  - Immobilize the fluid within the pore spaces
- Etc.

Cheung and Beirut, Journal of Petroleum Technology, 1985

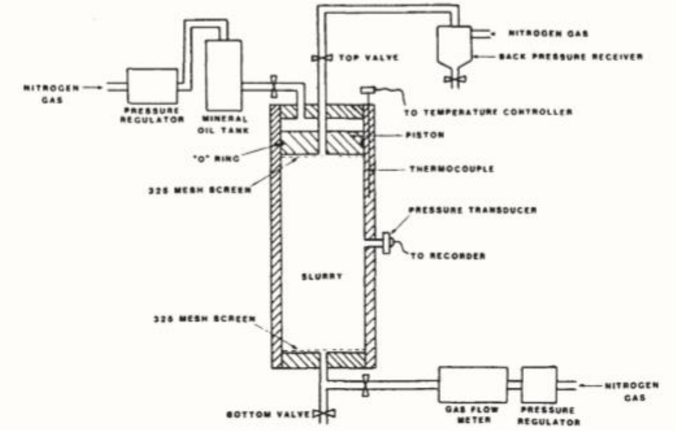


Fig. 1—Gas flow simulator.

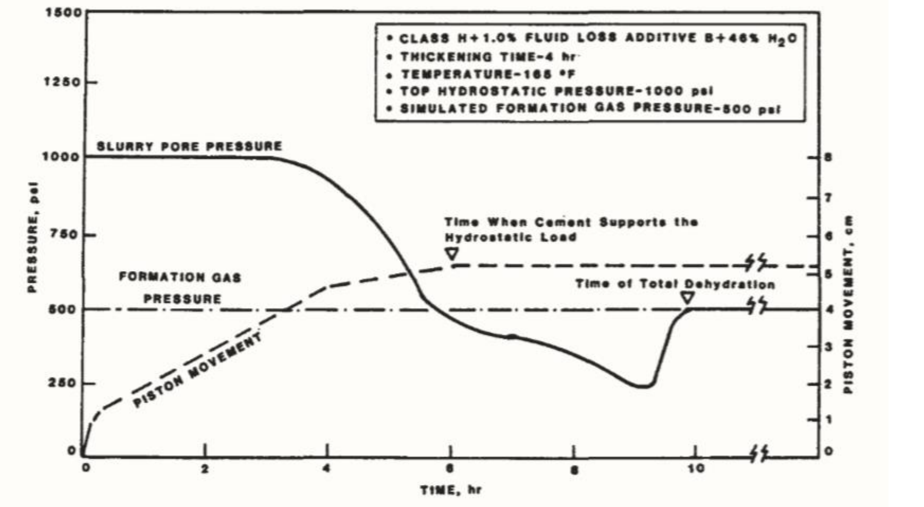


Fig. 4—Pore pressure vs. time in a slurry containing fluid-loss additive.

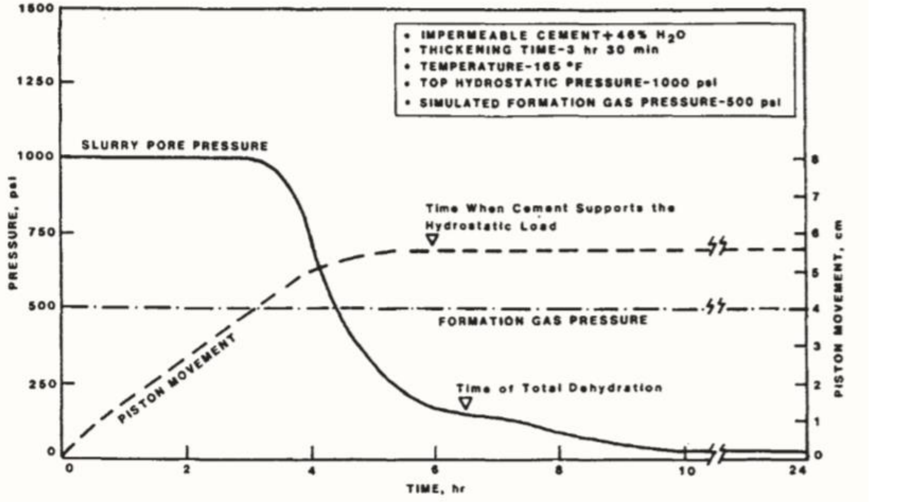
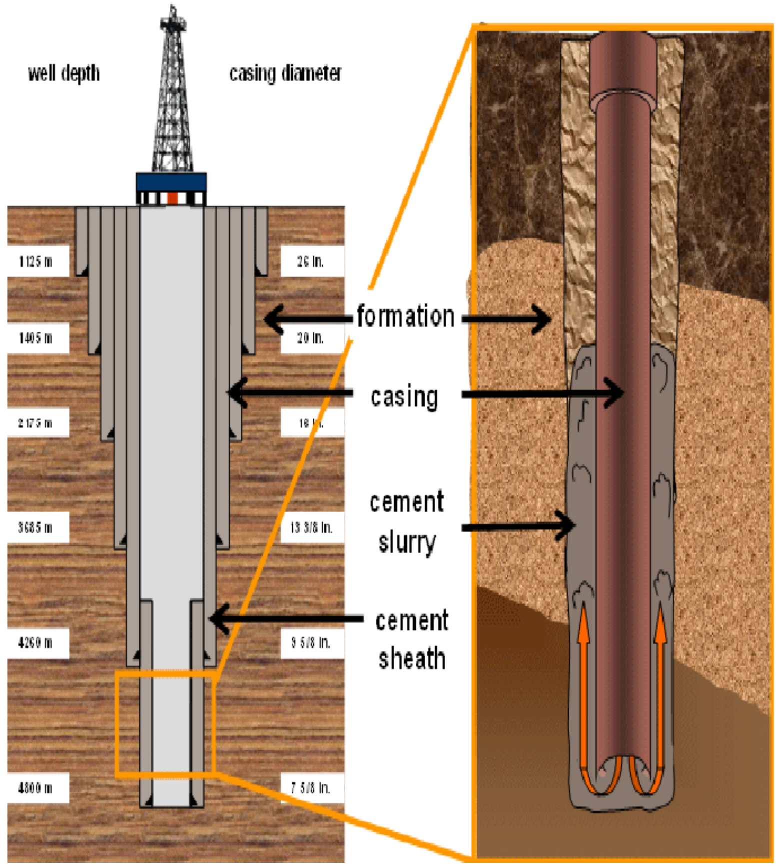


Fig. 7—Pore pressure vs. time in an impermeable cement system.

Objectives

- Develop a computer model for gas migration in well cement
- Simulate gas bubble motion in cement paste
- Provide a better understanding of the gas migration process in well cement
- Develop a computational model for cement slurry injection



http://www.drillingcourse.com/2015/12/introduction-to-cementing.html

Modeling

Numerical Approach

- Assumed two-phase flows
- The VOF multiphase model of ANSYS-Fluent

$$\frac{1}{\rho_{\mathrm{q}}}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = S_{\alpha_q} + \sum_{p=1}^{n} (\dot{m}_{\mathrm{pq}} - \dot{m}_{\mathrm{qp}})\right]$$

$$\rho = \alpha_2 \rho_2 + (1 - \alpha_2)\rho_1 \qquad \sum_{q=1}^{n} \alpha_q = 1$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \vec{v} + \nabla \vec{v}^{\mathrm{T}}\right)\right] + \rho \vec{g} + \vec{F}$$

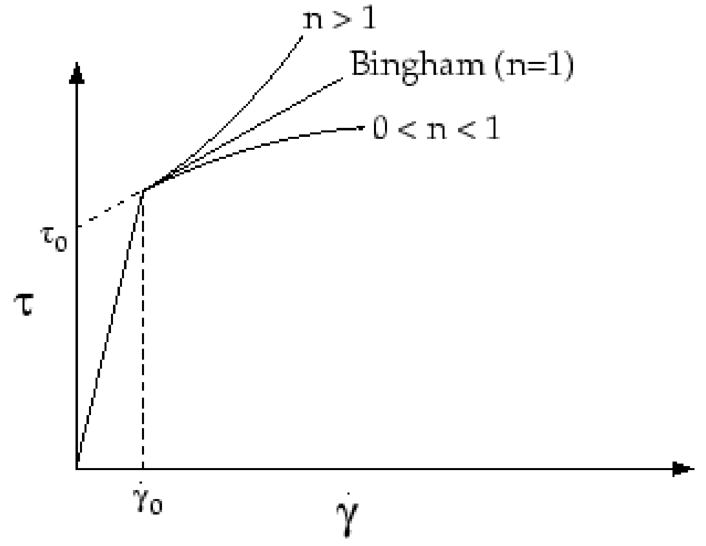
Rheological Model

$$\bar{\bar{\tau}} = \bar{\bar{\tau_0}} + \eta D$$

Herschel-Bulkley Model

$$\eta = \frac{\tau_0}{\dot{\gamma}} + k\left(\frac{\dot{\gamma}}{\dot{\gamma}_c}\right)^{n-1} \quad \text{if} \quad \dot{\gamma} < \dot{\gamma}_c$$

$$\eta = \frac{\tau_0\left(2-\frac{\dot{\gamma}}{\dot{\gamma}_c}\right)}{\dot{\gamma}_c} + k\left[(2-n) + (n-1)\frac{\dot{\gamma}}{\dot{\gamma}_c}\right] \quad \text{if} \quad \dot{\gamma} > \dot{\gamma}_c$$



Properties		
Liquid	Cement Slurry	Drilling Fluid (Water)
Density (kg/m^3)	1200	998
Surface Tension (N/m)	0.07	0.07
Rheological Model	Herschel-Bulkley Model	Linear Newtonian
Viscosity (kg/ms)	-	1×10^{-3}
Consistency Index (k) (kgs^{n-2}/m)	0.6	-
Power-Law Index (n)	0.4	-
Yield Shear Stress τ_0 (Pa)	1.4	-
Critical Shear Rate $\dot{\gamma}_c$ (1/s)	5.5	-

Results

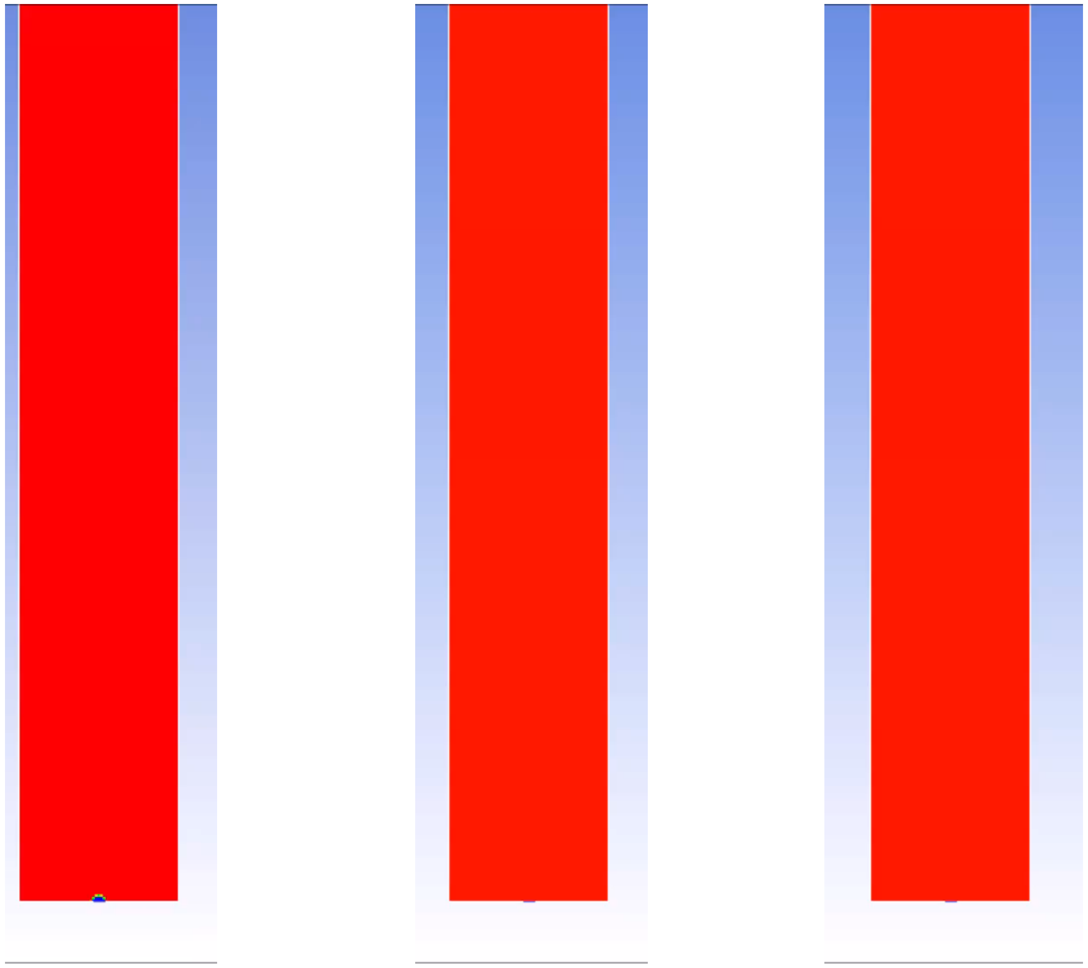
Gas Migration

2D Channel with Flat Walls

Geometry	
Length (m)	1
Width (cm)	6
Air Inlet Size (mm)	5

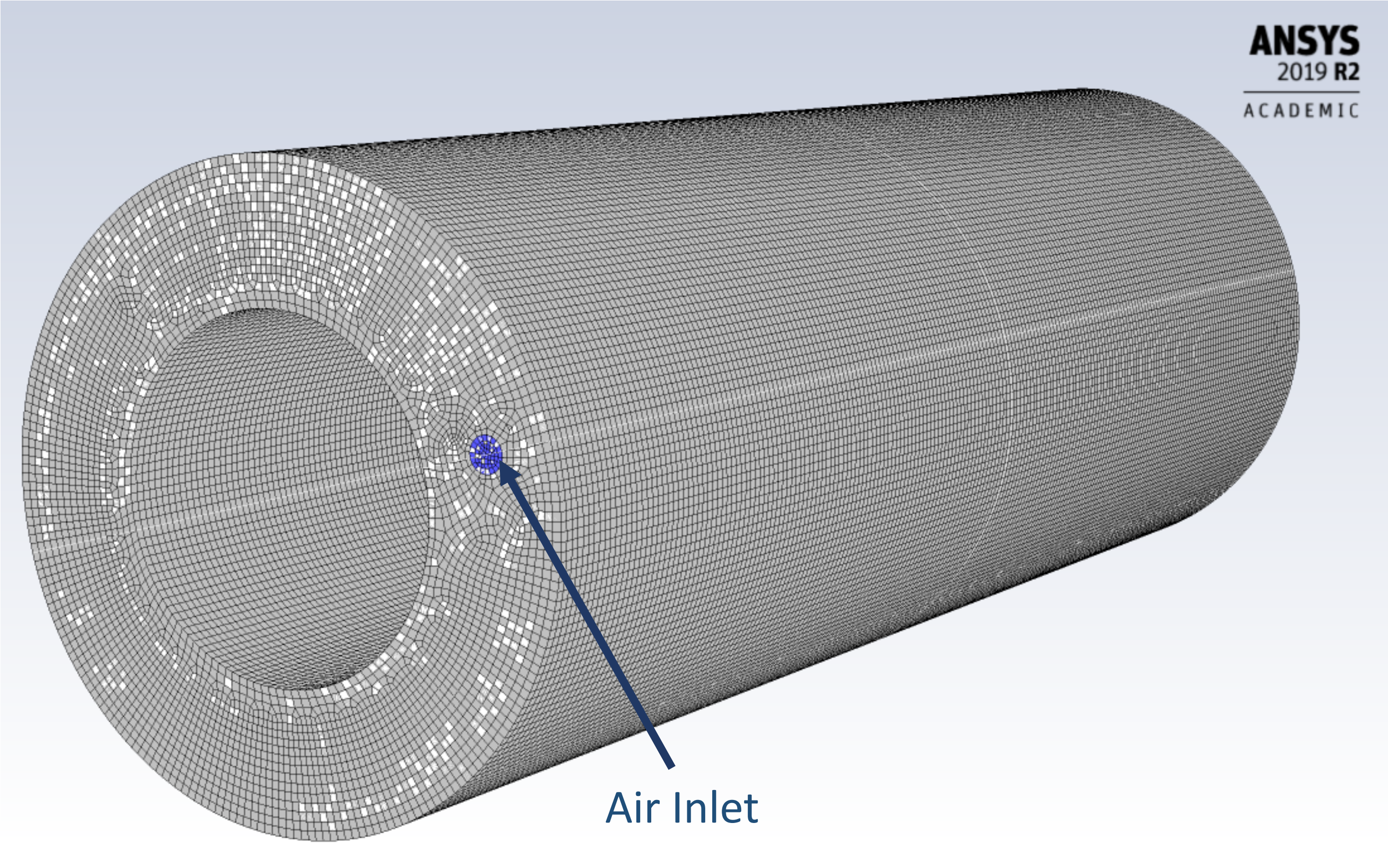
Cement Slurry Properties	
Viscosity (kg/ms)	1
Density (kg/m^3)	998
Surface Tension (N/m)	0.07

Slurry Model: Newtonian



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

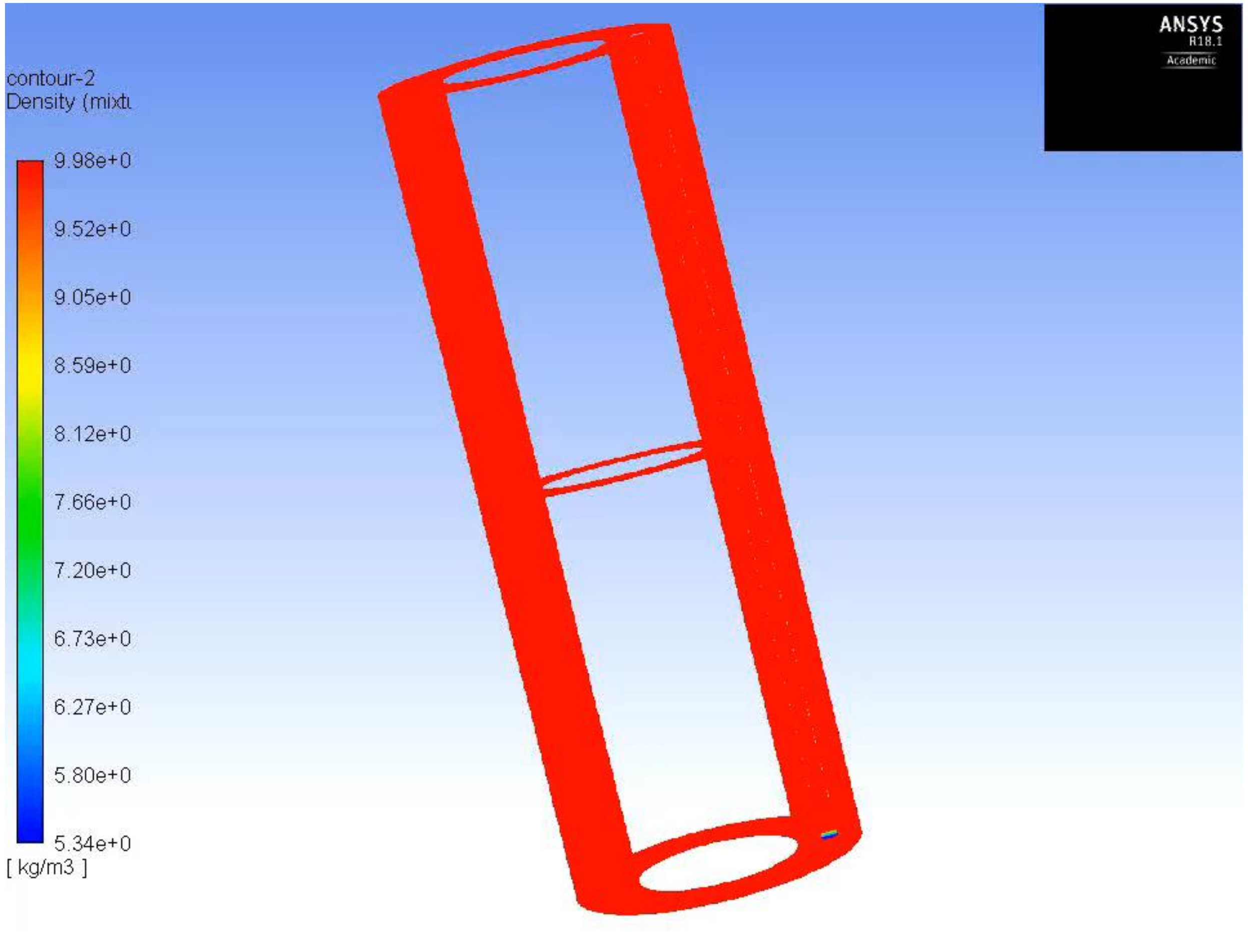
Gas Migration



Cylindrical Geometry

Length (m)	1
Inner Diameter (cm)	20
Outer Diameter (cm)	36
Air Inlet Diameter (cm)	1
Number of Elements	770,511

Gas Migration



V = 0.5 (m/s)

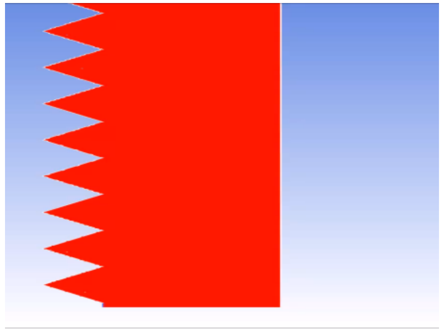
Cylindrical Geometry

Liquid Properties	
Viscosity (kg/ms) (Honey)	10
Density (kg/m^3)	998
Surface Tension (N/m)	0.07

Slurry Model: Newtonian (High Viscosity)

Gas Migration

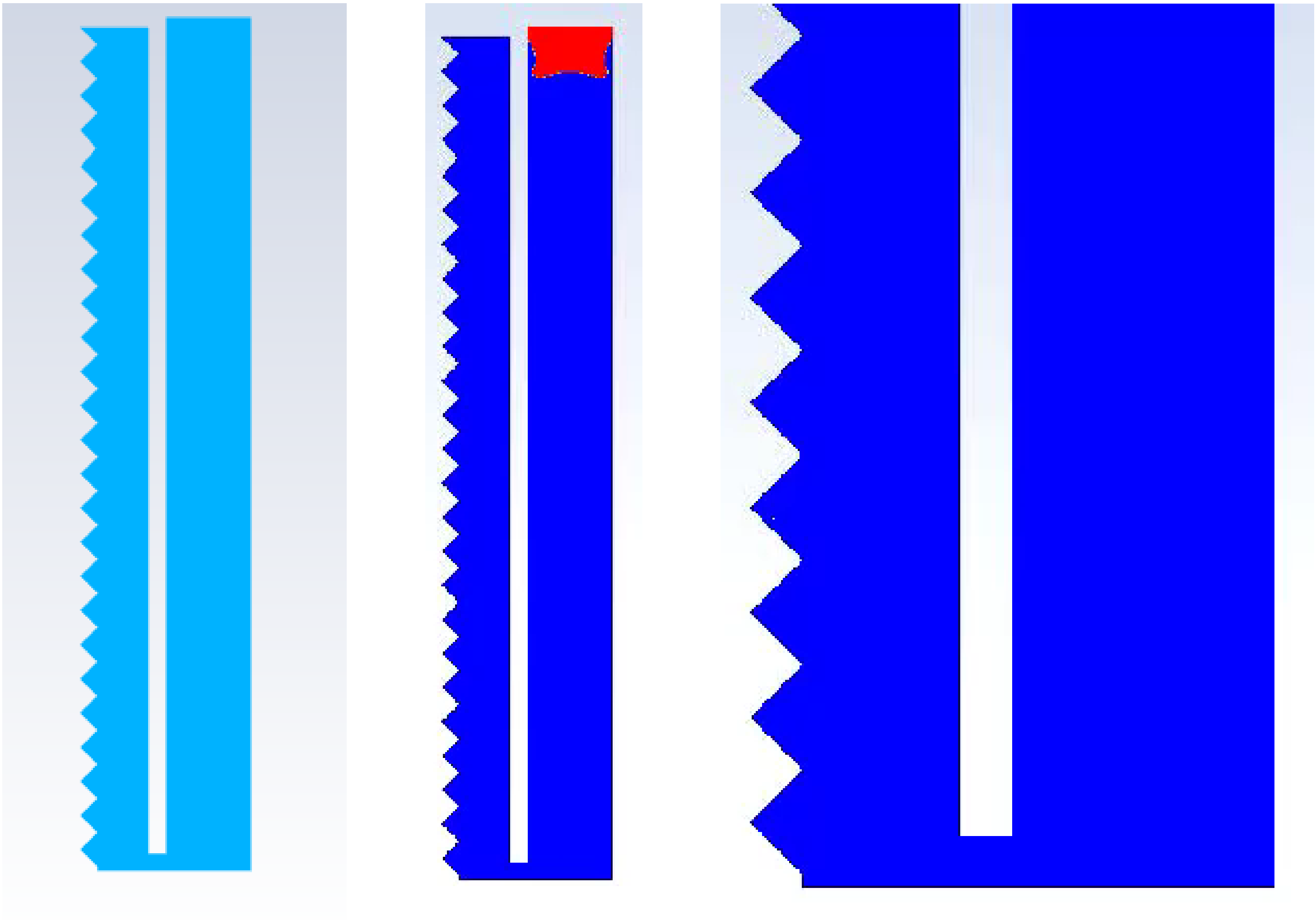
Irregular Wall Shapes 2-D



Liquid Properties	
Viscosity (kg/ms)	1
Density (kg/m^3)	998
Surface Tension (N/m)	0.07

Model: Newtonian
(Moderate Viscosity)

Cement Injection Modeling

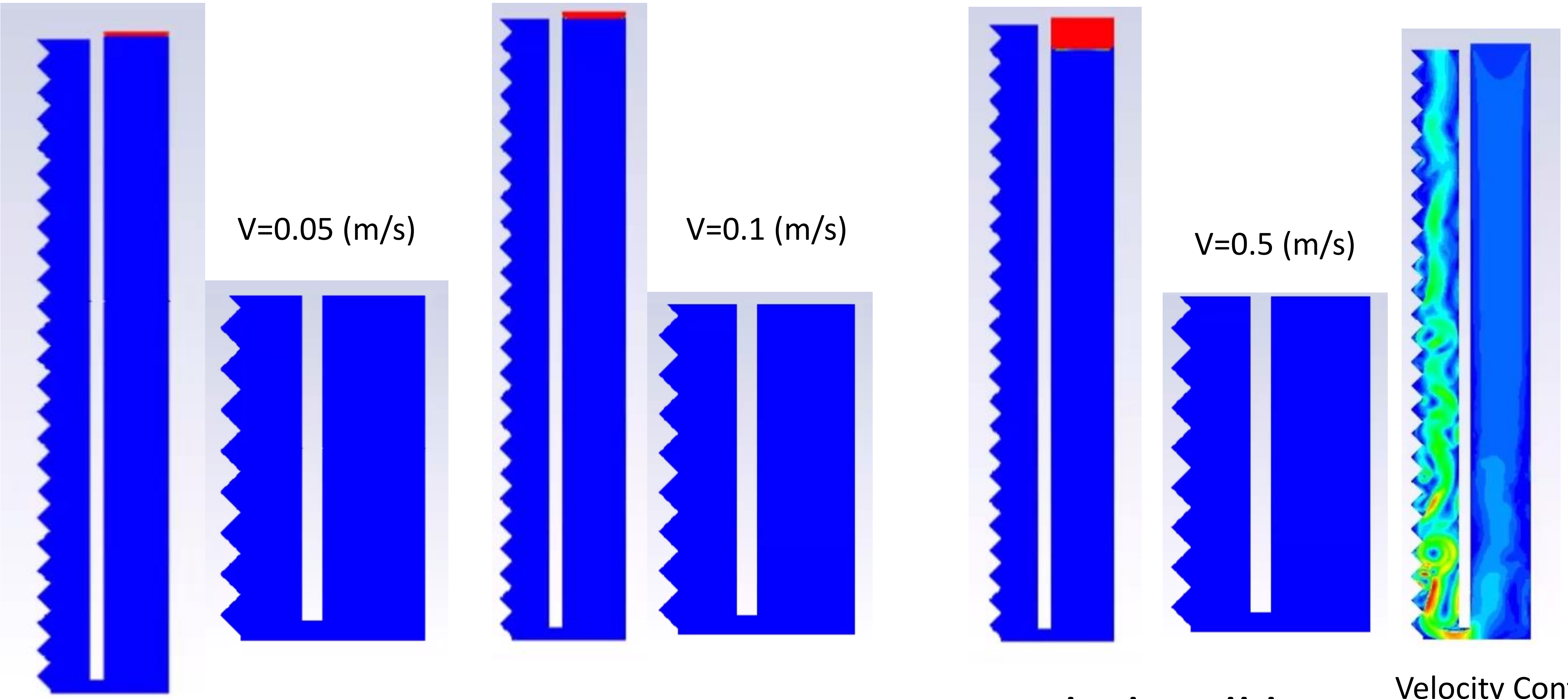


Irregular Wall Shapes 2-D

Liquid Properties	
Viscosity (kg/ms)	1
Density (kg/m^3)	998
Surface Tension (N/m)	0.07
Cement Inlet Velocity (m/s)	0.5

Models
Cement: Herschel-Bulkley
Drilling Fluid: Newtonian

Cement Injection Modeling

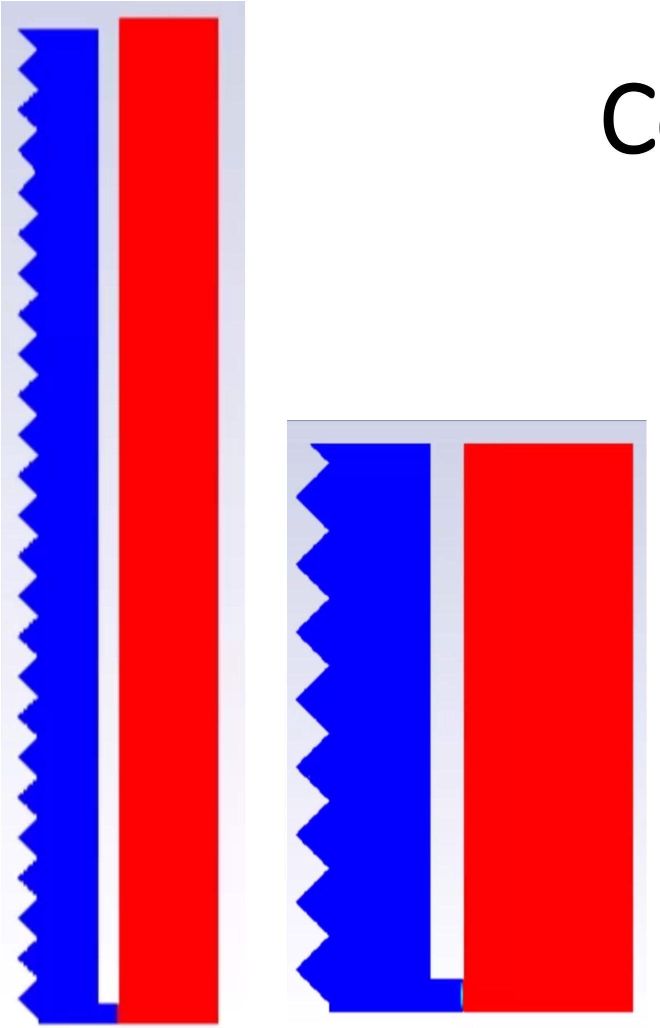


Velocity Contours

Sample Simulations

Cement: Herschel-Bulkley
Drilling Fluid: Newtonian

Cement Injection Modeling



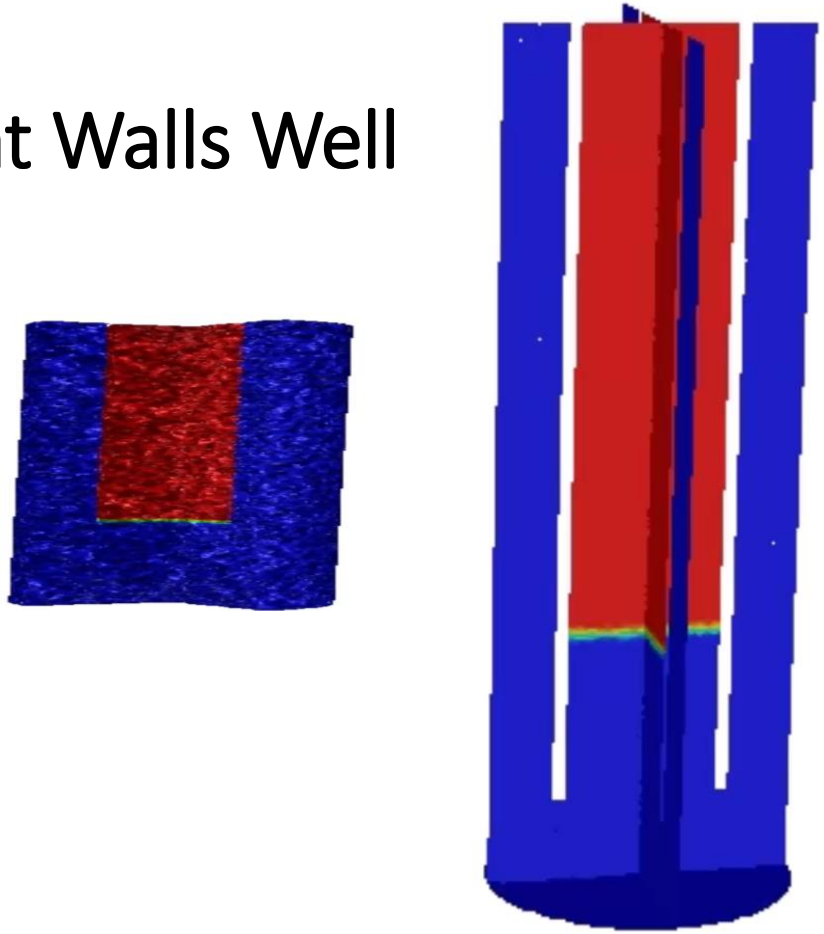
Cement Patched in the Tube

Models
Cement: Herschel-Bulkley
Drilling Fluid: Newtonian

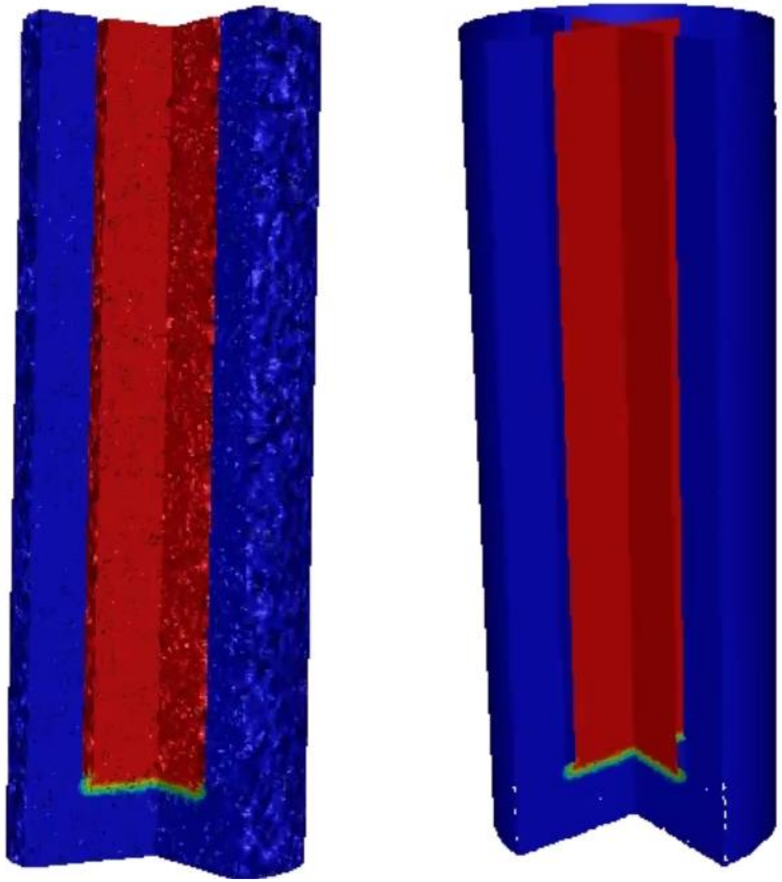
Cement Injection Modeling

3D Flat Walls Well

Inlet Velocity =0.05 m/s



Inlet Velocity =0.2 m/s



Conclusions

- A VOF model for gas bubble motion in cement was developed.
- The Newtonian and Herschel-Bulkley models was used for cement slurry.
- Simulations were presented to 2-D flat and rough wall as well as annulus well cement models.
- CFD could provide insight into the gas migration process.
- Further studies of the gas migration process is needed.

Future Works

- Model cement pastes as non-linear fluids exhibiting viscoelasticity, thixotropy, yield stress, shear-thinning effects (Tao et al. 2020, 2021)
- Include the reduction of pore pressure using empirical models
- Simulate the fluid migration as the pore pressure reduces
- Develop a rheological model including the pore pressure reduction
- Develop a constitutive law for cement paste solidification process

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