CFD Simulations of Horizontal Wellbore Cleaning and Cement Placement Processes in Drilling and Completions Applications for Petroleum Engineering

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- **Computational Resources**: HPC@LSU, Louisiana Optical Network Initiative (LONI), CCT, Petroleum Engineering Department

- **Related Publications**:
  - Zulqarnain, M., Simulations of the Primary Cement Placement in Annular Geometries during Well Completion Using Computational Fluid Dynamics (CFD), LSU MS Thesis (2012).
Outline

• Overview: Range of length scales in petroleum engineering applications

• Primary Cement Placement Simulation
  — Challenges
  — Simulation Procedure, V&V
  — Parametric Study

• Cuttings Transport in Deviated Wellbores
  — Challenges
  — Simulation Procedure, V&V
  — Parametric Study

• Concluding Remarks
  … and Future Directions
Range of length scales in PETE applications

- Sub-pore scale: $10^{-9} - 10^{-6}$
- Pore scale: $10^{-7} - 10^{-4}$
- Core-plug scale: $10^{-4} - 10^{-2}$
- Wellbore scale: $10^{-2} - 10^3$
- Reservoir scale: $10^1 - 10^3$

1 Length scale = 1 m

Ref: Deepwater Horizon Accident Investigation Report Appendix W
RELEVANT SCALES FOR FULL WELLBORE GEOTHERMAL RESERVOIR SIMULATION

Concept

Reservoir Simulation (~ 1km)

Image-based Porescale Simulation (~ 1µm)

Wellbore CFD Simulation (~ 1m)
Non-Newtonian Fluid Displacement during Primary Cementing

- Complete and permanent zonal isolation
- Complete removal of drilling mud
- Mud Channels
- How to remove mud?
- Direct contact of mud and cement
- Spacers

Factors affecting cementing job*

- Mud conditioning
- Flow rate
- Casing movement
- Eccentricity
- Mud filtration

*Chief Counsel’s Report 02/17/2011


Motivations/Objectives

- To fill some of the gaps present in terms of quantifications of the whole displacement process.

- The root technical cause of the blowout is now clear*: "The cement that BP and Halliburton pumped to the bottom of the well did not seal off hydrocarbons in the formation".

Objective

- Better understand the complex fluid displacement process and quantification (correlation) of the displacement process in terms of rheological properties of fluids involved under different borehole configurations.

*Chief Counsel's Report 02/17/2011
Validation and Verification

Displacement efficiency = (Cement/total volume of channel)

Numerical Setup

- Computational Fluid Dynamic (CFD)
- Volume of Fluid (VOF) method\(^1\)
- Interfacial reconstruction scheme\(^2\)
- Power Law/ Herschel Bulkley
- Laminar/ Turbulent flow

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2- Fluent 6.3 user manual
Simulation Setup

- Geometric details are taken from (D.J. Guillot et al. 2007)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Casing OD (in)</strong></td>
<td><strong>9.675</strong></td>
</tr>
<tr>
<td><strong>Open hole dia (in)</strong></td>
<td><strong>12.597</strong></td>
</tr>
<tr>
<td><strong>Annular length (ft)</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

- Fluid Properties (Wilson & Sabins 1988)

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>K(eq. cp)</th>
<th>ρ(lbm/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement</strong></td>
<td>0.308</td>
<td>4708</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>Mud</strong></td>
<td>0.607</td>
<td>1346</td>
<td>13.1</td>
</tr>
</tbody>
</table>
Results Interpretation

- **Spacer**
- **Mud**

**ps=pm , Re=167**

**Volume fraction**

- **Spencer**
- **Mud**
- **Cement**

**Annular volume sweeps**

- 0.25
- 0.5
- 0.75
- 1

**Inlet**

- 100 ft
- 10 ft
Challenges: Interfacial Instabilities

- **Rayleigh Taylor Instability:** Lighter Fluids acceleration into heavier fluid results in Rayleigh Taylor Instability, Rayleigh (1882), Taylor (1950)

- **Saffman-Taylor Instability:** Displacement of more viscous fluid by less viscous results in Saffman-Taylor instability, Saffman and Taylor (1958)


Prof. J. Hertzberg

Density Variations

(a) 

(b) 

(c) 

- $\rho_s = \rho_w, Re=167$
- $\rho_s = \rho_m, Re=167$
- $\rho_s = \rho_c, Re=167$

Mud Volume Fraction $\rho_s = \rho_w, Re=167$
- a) 0.14 $\varphi_e = 0.83$
- b) 0.13 $\varphi_e = 0.93$
- c) 0.03 $\varphi_e = 0.95$
- d) 0.01 $\varphi_e = 0.99$
- e) 0.00 $\varphi_e = 1.00$

Mud Volume Fraction $\rho_s = \rho_m, Re=167$
- a) 0.13 $\varphi_e = 0.84$
- b) 0.09 $\varphi_e = 0.89$
- c) 0.03 $\varphi_e = 0.96$
- d) 0.01 $\varphi_e = 0.99$
- e) 0.00 $\varphi_e = 1.00$

Mud Volume Fraction $\rho_s = \rho_c, Re=167$
- a) 0.08 $\varphi_e = 0.56$
- b) 0.10 $\varphi_e = 0.65$
- c) 0.14 $\varphi_e = 0.65$
- d) 0.11 $\varphi_e = 0.81$
- e) 0.01 $\varphi_e = 0.97$
Viscosity Variation

(a) \( \mu_s = \mu_w, Re=167 \)

(b) \( \mu_s = \mu_m, Re=167 \)

(c) \( \mu_s = \mu_c, Re=167 \)
CFD Based Correlation

Due to the nature of fluid being used the correlation is expected to be of the form of power law

\[ \varphi_c = \gamma \rho^a \mu^b Re^c \]  

(1)

Where \( \varphi_c \) is the cement volume fraction, \( \gamma \) is a constant multiplier,

\[ \rho = \frac{\rho_s}{\sqrt{\rho_m \cdot \rho_c}} \quad \mu = \frac{\mu_s}{\sqrt{\mu_m \cdot \mu_c}} \]

\( Re \) is the Reynolds number and \( a, b, c \) are constants.

<table>
<thead>
<tr>
<th>Variable</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( \gamma_1 )</th>
<th>( \gamma_2 )</th>
<th>( \gamma_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.0113</td>
<td>-0.0376</td>
<td>-0.0304</td>
<td>0.87334</td>
<td>0.73899</td>
<td>0.91210</td>
</tr>
</tbody>
</table>

\[ \varphi_c = 0.86705 \cdot \rho^{-0.0113} \cdot \mu^{-0.0376} \cdot Re^{-0.0304} \quad (\text{For } \rho_s < \rho_c, \mu_s < \mu_c) \]  

(2)

\[ \varphi_c = 0.74692 \cdot \rho^{-0.0113} \cdot \mu^{-0.0376} \cdot Re^{-0.0304} \quad (\text{For } \rho_s = \rho_c, \mu_s = \mu_w) \]  

(3)

\[ \varphi_c = 0.91176 \cdot \rho^{-0.0113} \cdot \mu^{-0.0376} \cdot Re^{-0.0304} \quad (\text{For } \mu_s = \mu_c, \rho_s = \frac{\rho_c + \rho_m}{2}) \]  

(4)

The value of \( R^2 \) was found to be 0.975, which shows a reasonable fit.
Concluding Remarks

• If cement and mud are compatible to each other than the fresh water will be the most effective means of displacing mud and detaching the adhered mud layer to walls

• If cement and mud are incompatible than a spacer with density equal to that of mud and viscosity of fresh water will be most effective

• For vertical well the final cement fraction slightly decreases with increasing displacement rate for spacer having density less than cement, while for the spacer density equal to cement the opposite is true

• CFD offers good tools to model complex fluid displacement processes, more complexities can be incorporated in future studies like variable bore hole, effect of temperature, modeling for the entire length using moving meshes etc.

• Other simulations (not presented here) – Horizontal wellbores, Varying rheology, Varying displacement rates.
Future Directions (Component scale applications)

- Cement job in long horizontal wellbores
- Fluid displacement instabilities during 180° turn at the casing end
- Modeling foamed cement displacement (in contrast to H-B rheology)
- Multiphase turbulent flow simulations in petroleum engineering field equipment such as slotted liners, gravel packs etc.
- … and couple heat transfer, phase change etc. to improve the engineering design
Discrete Phase Simulations of Cuttings Transport in Highly Deviated Wellbores

- Physics of cuttings transport
- Review: Previous modeling approaches
- Computational model description, boundary conditions and simulation procedures
- Results – verification & validation, cuttings bed height & moving bed velocity estimation, parametric study
- Discussions
- Conclusions and future directions
Cuttings Transport Mechanisms and Issues at Different Wellbore Inclinations

**0 - 45 degrees**
- Vertical – Near Vertical Wellbores
- Particle Settling

**45 - 60 degrees**
- Critical Inclinations
- Downwards sliding of stationary bed

**60 – 90 degrees**
- Horizontal – Near Horizontal Wellbores
- Accretion on the low side

Main Transport Mechanism: Suspension

(Tomren et al, 1986)
Risks of High Solids Concentration in the Wellbore

- High torque and drag
- Poor hole condition
- Stuck pipe
- Difficulty in running and cementing casing
Parameters involved in Cuttings Transport Process

- Drillpipe Eccentricity
- Mud Weight
- Cuttings Density
- Hole Size and Hole Angle
- Flow Rate
- Rheology
- Rate of Penetration
- Drill Pipe Rotation
- Hole Cleaning Pills

(Adari et al., 2000)
A cuttings transport model should predict the following:

• Maximum bed height for:
  - Optimizing drilling parameters for adequate wellbore cleaning.

• Particle velocities for:
  - Circulation time estimation
  - Solids concentration control

• Frictional pressure losses due to solids concentration
Numerical Setup Summary

A 3D model couples main fluid mass and momentum conservation with:

- Shear Stress Transport (SST) k-Omega Turbulence Closure
- Discrete Phase Model

Includes:

- Non-Newtonian Rheology
- Wall Roughness for Fluid Flow (Modified Law of the Wall)
- Turbulent Dispersion of Particles (Random Walk Model)
- Non-spherical particles (Modified drag coefficient)
Turbulent Flow of Non – Newtonian Fluids

Comparison of experimental data from Pereira and Pinho with CFD results. Experimental Setup:
- Pipe Radius: 26 mm
- Fluid: Water with 0.4% Tylose
- Rheology: Carreau Model
  \[ \lambda (s) = 0.0208, \mu_0 = 0.00407, n = 0.725 \]
- Mean Velocity: 5.59 m/s

Comparison of experimental data from Piho and Whitelaw with CFD results. Experimental Setup:
- Pipe Radius: 25.4 mm
- Fluid: Water with 0.4% CMC
- Rheology: Power Law
  \[ k=0.447, n=0.56 \]
- Mean Velocity: 4.8 m/s
Discrete Phase Model

• Governing Equation:

\[ \frac{\partial u_p}{\partial t} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \]

Includes non-spherical drag coefficient

- Drag Force Term
- Buoyancy Term

Additional forces: Pressure Gradient Force, Virtual Mass force (Force needed to accelerate the surrounding fluid)

Estimation of Cuttings Bed Height

For an accretion/erosion model following mechanisms should be known:

1. How does particles lose momentum upon impact?
2. How does particles accrete and form a bed?
# Particle-Fluid Interaction Forces

<table>
<thead>
<tr>
<th>Forces</th>
<th>Correlations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drag force</strong></td>
<td>For an isolated particle moving through a gas, $F_d = C_d \pi \rho_f d_p^2</td>
<td>u - v</td>
</tr>
<tr>
<td></td>
<td>Effect of surrounding particles is described by a voidage function, $f(\varepsilon_f)$: $F_d = f(\varepsilon_f) C_d \pi \rho_f d_p^2</td>
<td>u - v</td>
</tr>
<tr>
<td></td>
<td>$C_d = 24(1 + 0.15 Re_p^{0.687}) / Re_p (Re_p &lt; 1000)$</td>
<td>Erkun (1952), and Wen and Yu (1966)</td>
</tr>
<tr>
<td></td>
<td>$C_d = 0.44(Re_p &gt; 1000)$</td>
<td>Di Felice (1994)</td>
</tr>
<tr>
<td></td>
<td>$f(\varepsilon_f) = \varepsilon_f^{(a+1)}$</td>
<td>Koch and Sangani (1999), and Koch and Hill (2001)</td>
</tr>
<tr>
<td></td>
<td>$\alpha = 3.7 - 0.65 \exp[-(1.5 - \log Re_p)^2 / 2]$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F = F_0(\phi) + F_1(\phi) Re_p^2 (Re_p &lt; 20)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F = F_0(\phi) + F_3(\phi) Re_p^2 (Re_p &gt; 20)$</td>
<td></td>
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<tr>
<td></td>
<td>$F_0(\phi) = \frac{1 + 3(\phi/2)^{1/2} + (135/64) \ln \phi + 16.14 \phi}{1 + 0.681 \phi - 8.48 \phi^2 + 8.16 \phi^3} (\phi &lt; 0.4)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_0(\phi) = 10\phi / (1 - \phi)^3 (\phi &gt; 0.4)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_1(\phi) = 0.110 + 5.10 \times 10^{-4} \phi^{11.5 \phi}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_3(\phi) = 0.0673 + 0.212 \phi + 0.0232 (1 - \phi)^5$</td>
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</table>

**Pressure gradient force**

It is of general validity and all relevant contributions are included when $d\rho / dx$ is evaluated from the fluid equation of motion.

<table>
<thead>
<tr>
<th>Force</th>
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<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual mass</td>
<td>$F_{Vm} = C_{vm} \rho_f V_p (\dot{u} - \dot{v}) / 2$</td>
<td>Odar and Hamilton (1964), and Odar (1966)</td>
</tr>
<tr>
<td>Mass</td>
<td>$C_{vm} = 2.1 - 0.132 / (0.12 + A c^2)$</td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>$A_c = (u - v)^2 / (d \rho_f (u - v) / dr)$</td>
<td></td>
</tr>
</tbody>
</table>

**Basset force**

$F_{\text{Basset}} = \frac{3}{8} d_p^2 \pi \rho_f | u - v| \left[ \int_0^t \frac{(u - v)(v - v)'}{\sqrt{t'}} dt' + \frac{(u - v)h}{\sqrt{t}} \right]$

where $(u - v)h$ is the initial velocity difference

**Saffman force**

$F_{\text{Saff}} = 1.61 d_p^2 (\mu_f \rho_f)^{1/2} | c |^{-1/2} [ (u - v) \times c ]$

**Magnus force**

$F_{\text{Magn}} = \frac{1}{2} d_p^2 \rho_f \left[ \left( \frac{1}{2} \nabla \times u - \omega_d \right) \times (u - v) \right]$

where $\frac{1}{2} \nabla \times u$ is the local fluid rotation and $\omega_d$ is the particle rotation. One notes that the lift would be zero if the particle rotation is equal to the location rotation of the fluid.

Hypotheses for Equilibrium Cuttings Bed Height
Particle-Wall Interactions

Hypotheses based on experimental observations of particle-wall collisions:

With increasing flow rate and decreasing accumulation rate, the following should be observed:

1. Increase in P-W IMPACT VELOCITY
2. Decrease in TOTAL NUMBER OF P-W COLLISIONS
3. Decrease in MAXIMUM P-W IMPACT ANGLE
4. Increase in DISTANCE COVERED IN SUSPENSION
Particle – Wall Collision Analysis

Bulk velocity: 1 ft/sec:

Bulk velocity: 2 ft/sec:

Bulk velocity: 3 ft/sec:

Bulk velocity: 4 ft/sec:

Bulk velocity: 5 ft/sec

Fluid Velocity

[ft s⁻¹]
Particle Track Analysis: P – W Impact Velocities

P-W Impact velocities at different bulk fluid velocities.

IMPACT VELOCITY increases with increasing flow rate

Particle Track Analysis
P – W Impact Angles

Number of collisions with different impact angles

- TOTAL NUMBER OF COLLISIONS decreases with increasing FLOW RATE
- MAXIMUM IMPACT ANGLE decreases with increasing FLOW RATE
Particle Track Analysis: Distance Covered in Suspension

Example:

Percentage Horizontal distance covered between norm. vertical distances 0.4 and 0.5:

\[ \frac{[ L_1 + L_2 + L_3 ]}{\text{Total Distance}} \]
Particle Track Analysis
Distance Covered in Suspension

Percentage of Distance Covered

Vertical Distance from the Bed Surface, mm

- 1 st/sec
- 2 ft/sec
- 3 ft/sec
- 4 ft/sec
- 5 ft/sec
Experimental Test Matrix: (Garcia – Hernandez et al.)

Experimental Setup:
• Geometry: 8” x 4.5” concentric Annulus
• Carrier Fluid: Water
• Particles: Gravel
• Particle Size: 3 – 5 mm
• Particle Specific Gravity: 2.6

Experimental Procedure:
• After flow is stabilized (Periodic) solid particles are injected from one end of the flow loop.

• After the stationary bed reached an equilibrium (No change) bed heights are measured on different points.

• Bulk velocities are calculated by dividing the flow rate to the decreased flow area by the bed.

• Velocities of marked particles are measured by image velocimetry method.

• Particle velocities are averaged until no change in the average.
300 gpm – 70 degrees Wellbore Inclination

Continuous turbulence K. E. buildup over bed surface
300 gpm – 70 degrees Wellbore Inclination

Hypotheses # 1/3:
Particles are moving in the bulk suspension

Averaged impact velocities
300 gpm – 70 degrees Wellbore Inclination
Distance Covered in Suspension

Particle suspension increases significantly at ABH
300 gpm – 70 degrees Wellbore Inclination

Particle – Wall Collisions

Particle – Wall collisions nearly vanished at ABH
Unsteady Particle Tracking: Particles are injected and particle paths are calculated at every time step.

Assumptions:

1. Sphericity is uniform and has the value 0.1 for all particles

2. Stationary bed height reached equilibrium, flow shear compensates for momentum loss due to particle-wall collisions.
Moving Bed Velocity Validation

Experimental Results (Data from Garcia – Hernandez et al., 2007)

- Fluid Velocity, ft/sec
- Moving Bed Velocity, ft/sec

- Sphericity = 0.1, Size distribution: Uniform
Model Limitations

• DPM and SST k-ω turbulence model are coupled in a one way fashion in which the effects of particle motion on flow field is neglected.

  *Model is not responsive to solids loading (or ROP). The effects of solids on frictional pressure losses are discarded.*

• Particle – particle interactions are also neglected assuming solids concentration is low enough.

  *However, P-P interaction forces can be important in cases where accurate particle shape information is available.*
Model Limitations

• Suspension levels in cases with inner pipe rotation were not as high as described in experimental works. Orbital movement of the pipe and vibrations should also have K. E. contributions to the flow.

• Particle size distribution is found to have negligible effect on the moving bed velocity. It can be influential in wider ranges.

• Two-equation turbulence models can not capture transient regimes where molecular viscosity and eddy viscosity can be equally effective.
Concluding Remarks

• Accurate prediction of velocity profiles of non-Newtonian fluids flowing in turbulent regime.

• Accurate prediction of stationary bed heights in horizontal wellbores with different flow rates, inclined wellbores and wellbores with inner pipe rotations. The effects of wellbore inclination and inner pipe rotation are in agreement with experimental observations through validation.

• Accurate prediction of average moving bed velocity.

• Qualitative sensitivity studies are conducted for fluid density, rheology, particle sphericity and size distribution and inner pipe rotation speed (Not presented here).
Future Directions (Cuttings Transport)

- Full wellbore flow path
- Coupling of particle-wall interactions (DEM)
- Morphology of cuttings bed
Questions

Calvin and Hobbes by Bill Waterson