Modeling Frac-Fluid Rheology & Leakoff

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In this session ...

• Selection of frac fluid and generic fluid types
• Basic descriptions of fluid behavior
• Basic interpretation of lab & field tests
Selecting Fracturing Fluids

• Desired properties of frac fluids
  – Non-damaging
    • Leave no residue behind
    • Do not cause capillary or phase trapping
  – Low friction in pipe
  – Sufficient viscosity to transport proppant
    • Yield viscosity quickly
    • Maintain viscosity at shear and temperature
  – Clean breaking
    • Break after desired time at temperature
    • Break to low viscosity and no yield-point
  – Low (or controlled) fluid loss
Aqueous polymer solutions

• Guar gum
  – Made from guar beans
  – High molecular weight mannose and galactose sugars (polysaccharides)
  – Frequently high residue (6-10%) but can be processed

• Hydroxypropyl Guar, HPG
  – Derivative of guar
  – Lower residue (2-4%) and more soluble in alcohol
  – More stable at higher temperatures
  – Similar formation damage to guar
Aqueous Polymers

• Hydroxyethylcellulose, HEC
  – Glucose backbone
  – Cleaner fluid than guar or HPG
  – Difficult to crosslink

• Carboxymethyl-Hydroxypropyl Guar, CMHPG
  – Popular as a high temperature base gel
  – Frequently crosslinked with Zr

• Carboxymethyl Guar, CMG
  – Yields viscosity in fresh water
  – Intolerant to salts
Water-Based Foam Systems

• CO$_2$ water-based “foams”
  – CO$_2$ density is close to water
  – More an emulsion than a foam
  – High CO$_2$ solubility in water
  – Good cleanup from CO$_2$ flashing

• N$_2$ foamed water-based gels
  – Low density and high friction (high WHTP)
  – Less efficient proppant transport
  – Useful in low pressure gas reservoirs for lift
  – Added flowback energy for cleanup in tight zones

• Binary foams (CO$_2$ + N$_2$)
  – Benefits of CO$_2$ solubility
  – Disadvantages of N$_2$ density
Oil-Based Fluids

- Various base-oil formulations
  - Diesel
    - Seasonal variations, often have added surfactants
  - Lease crude
    - Wide range of compositions, danger of precipitation and damage
  - Condensate
    - Safety concerns with volatility and flash point
  - Frac oils (FracSol, etc.)
    - Clean and easy to crosslink but expensive
  - Gelled LPG (Propane and Butane)
    - Pressurized blenders and limited job size
Surfactant based Systems

• Non-polymer (no solids or residue)
• Generate viscosity from fluid structure in hydrocarbon-water micro-emulsion
• Poly-emulsion fluids (oldest type)
  – Use surfactants to generate a stable oil-water emulsion
• Micellar fluid systems (ClearFrac)
  – Cationic surfactant
  – Generates long “rod-like” micelles
  – Breaks when hydrocarbon content increases
• Micro-vesicle fluids
  – Generate larger spherical “droplets”
  – Contain internal breakers
Crosslinkers

- **Water based systems**
  - **Borate ion**
    - Temporary and regenerative crosslinker
    - Crosslink reforms after shearing
    - Ion yield and stability controlled by pH
    - Requires high pH (9-12) for viscosity yield
  - **Zirconate**
    - Stable at high temperatures
    - Low pH crosslink is stable (can be used with CO₂)
    - A “one-time” chemical bond between polymer molecules
    - Sensitive to shear, will not re-link
  - **Titanate**
    - Shear sensitive metallic crosslinker
  - **Aluminate**
    - Not as commonly used
Breakers (and De-Linkers)

- Breakers attack the polymer backbone and break it into smaller molecular weight fragments
- The total mass of polymer remains the same
  - Viscosity of polymer suspension decreases
  - Filter cake remains and becomes more compressed
- De-linkers attack the crosslink sites but leave the polymer intact
  - Most commonly these are pH adjusters used with borates
Fracturing Fluid Rheology

- Fracturing fluids are complex, non-Newtonian fluids
- Their properties are affected by shear rate, shear history, minor additive concentrations, proppant types, temperature, mix water chemistry, age of chemicals, and many other factors
- Their properties are very difficult to quantify
Power Law Rheology Model

Describes the behavior of “shear thinning” fluids

The slope of the line is determined by \((n' - 1)\)

The magnitude of viscosity is determined by \(k'\)

\[
\mu = 47879k'\gamma^{n'-1}
\]
Fluid Properties are Dependent on Measurement Geometry

- Couette (Bob-and-cup)
  - B2
  - B5X
- Cone-and-plate
- Pipe rheometer
- Helical screw rheometer
- Parallel-plate slot

Data is also dependent on shear-history, shear, and heat-up profile
Apparent Viscosity at 40/sec for Two Data Sets (Fann Couette Geometry)
Variation in $n'$ with Geometry

![Graph showing variation in $n'$ with Geometry]
Variation in $k'$ with Geometry
Power-Law Data Does Not Tell the Whole Story.

Data in this shear rate range determine fluid’s prop transport efficiency.

Two fluids with the same \( n' \) and \( k' \) may have very different properties.
Model Parameters

- Each fluid is characterized by four model parameters
  - $U_0$ = “zero shear” fluid viscosity, $\text{cp}$
  - $n'$ = Power Law rheology exponent
  - $k'$ = fluid consistency index (viscosity at 1.0 sec$^{-1}$)
  - $U_\infty$ = “high shear” viscosity in the upper Newtonian plateau (solvent viscosity)
- $\gamma_N$ = shear rate at the onset of the low-shear Newtonian plateau
  - Computed from intersection of power-law and Newtonan models
Definition of Carreau Parameters

\[ C_n = \text{normalized volume fraction solids} \]
\[ a = \text{slurry viscosity exponent (~1.8)} \]
Time-Dependent Fluid Modeling

• Each primary parameter is time dependent
  – K’, n’, Uo

• Additional Data
  – The viscosity at infinite shear rate is assumed to be the same as the minimum viscosity after break which is often about 150% of the viscosity of the base fluid at reservoir temperature.
  – The maximum value that n’ can increase to must be specified which is generally 1.
Fluid Break Model

Carreau Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U min</td>
<td>0.40</td>
</tr>
<tr>
<td>U zero</td>
<td>170.00</td>
</tr>
<tr>
<td>n'</td>
<td>0.60</td>
</tr>
<tr>
<td>n' max</td>
<td>1.00</td>
</tr>
<tr>
<td>gL</td>
<td>21.00 sec^{-1}</td>
</tr>
<tr>
<td>k'</td>
<td>0.012000 lb^2 s^{-2} n'^{-1}</td>
</tr>
</tbody>
</table>

Break Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction Time</td>
<td>2.4000</td>
</tr>
<tr>
<td>Time Exponent</td>
<td>1.50</td>
</tr>
<tr>
<td>Sharpness in the Break Curve</td>
<td>2.00</td>
</tr>
<tr>
<td>Yield Point</td>
<td>0.000 psi</td>
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</tbody>
</table>

Legend

<table>
<thead>
<tr>
<th>Curve Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carreau</td>
<td>Power Law</td>
</tr>
<tr>
<td>N' vs Time</td>
<td>K' vs Time</td>
</tr>
<tr>
<td>Yp vs Time</td>
<td></td>
</tr>
</tbody>
</table>

Reference Time (min)

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Graphs:

- Viscosity (cp)
- Shear Rate (sec^{-1})
- Time (min)
Break profile is affected by several parameters.
Effect of Gel Stabilizer on Break Profile
How Much Fluid Stability is Needed?

Induction time ~15 min

Break Rate as Fast As Possible

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Recommended Temperature Profile for Break Testing

- 75-80% BHST
- WHT+20F

- Pad
- First Sand
- Last Sand
Heat Flow in Fracture

- Radiation – low heat flow rate
- Conduction – inefficient in gas bearing porous media
- Convection – dominant mechanism
  - High fluid pressure in fracture drives leakoff
  - Leakoff carries heat away from fracture
- Crosslinked fluid minimizes fluid circulation and convection in the fracture
Correlations Approximate Observed Slurry Viscosity Increase

$C_{v_{\text{max}}} = 0.64$
Effect of Sand Addition on Frac Fluid Rheology

- 15 ppa
- 10 ppa
- 5 ppa
- 0 ppa

Shear Rate, 1/sec

Viscosity, cp

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Frac Fluid Rheology is Complex

- This overview barely skims the surface of frac fluid rheology
- The behavior of fluids during a job is complex, time dependent, temperature dependent, and affected by minute changes in water chemistry that sometimes cannot be identified by conventional analyses
- Work closely with the service provider and develop some trust and understanding, but institute a meaningful field QC program
Frac Fluid Loss: One-Dimensional Transient Flow

Distance from frac face

$P_{\text{frac}}$

$P_{\text{pore}}$
Typical Fracturing Fluid Loss

\[ C_v = 0.0469 \sqrt{\frac{k\Delta P \phi}{\mu_a}} \]
\[ C_c = 0.0374\Delta P \sqrt{\frac{k\phi c_t}{\mu_r}} \]
\[ C_w = 0.0164 \frac{m}{A} \]
\[ C_T = \frac{1}{C_v} + \frac{1}{C_c} + \frac{1}{C_w} \]

Does not consider shear of filter cake or invasion of whole gel into matrix, including non-Newtonian rheology.
Impact of Resistances in Series

\[ \Delta P_3 = \frac{L_3}{k_3} + \Delta P_2 = \frac{L_2}{k_2} + \Delta P_1 = \frac{L_1}{k_1} = \Delta P_T \]

\[ K_{\text{avg}} = \frac{L_t}{L_1/k_1 + L_2/k_2 + L_3/k_3} = 0.025 \]
Filtration Process

Fracture
Classical Filtration Modeling

\[ \text{Slope} = 2C_t \text{ where:} \]
\[
C_t = \frac{2C_c^* C_v^* C_w^*}{C_v^* C_w^* + C_v^{*2} C_w^{*2} + 4C_c^{*2} (C_v^{*2} + C_w^{*2})}
\]

with
\[
C_w^* = \frac{k_w S_w \Delta p_t}{2 \mu_w S_b}
\]

\[ \text{Slope} = 2C_{vc} \text{ where:} \]
\[
C_{vc} = \frac{2C_v^* C_c^*}{C_v^* + C_v^{*2} + 4C_c^{*2}}
\]

where
\[
C_c^* = \frac{k_c c_t \phi}{\pi \mu_c} \Delta p_t \text{ and } C_v^* = \frac{k_v \phi \Delta p_t}{2 \mu_v}
\]
Effect of Shear Rate
HPG at 2000 psi, 1 md

Volume per Area (ml/cm²)

Spurt Loss

2C� nửa

100 sec⁻¹

0 sec⁻¹

50 sec⁻¹

√Time (min)
Effect of Shear Rate

HPG+B, 2000 psi, 1 md

Volume per Area (ml/cm²) vs. √Time (min)
Forces Acting on Polymer Molecule

- Fluid Loss Gradient
- Shear Stress & Hydrodynamic Forces
- $P_{\text{fracture}}$
- Filter Cake
- $P_{\text{res}}$
Effect of Permeability and Shear

HPG+B, 1000 psi, 100-25 sec⁻¹

![Graph showing the effect of permeability and shear on volume per area (ml/cm²) over time (min). The graph includes lines for different permeability values: 311 md, 148 md, 14.9 md, 1.4 md, and 0.34 md.]
Effect of Filtration Pressure
HPG+B, 100 sec⁻¹, 100 md
Effect of Breaker
HPG + DB at 82 C, 100 md

Volume per Area (ml/cm²)

0 1 2 3 4 5 6 7 8 9 10

0 0.5 1 1.5 2 2.5 3 3.5 4

Time (min)

2.5 lb SP
1.0 lb SP
0.5 lb SP
No Breaker

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Influence of Fluid Properties and Temperature on Spurt Loss

- **Fluid Viscosity has a Dominant Affect**

- Increasing Temperature
  - ➔ Increase Vspt

- Increasing Breaker Concentrations
  - ➔ Increase Vspt

- Increasing Gel Concentration
  - ➔ Decrease Vspt
Influence of Fluid Props and Temp on Filter Cake Growth (Cw)

- Fluid Properties will dictate IF a filter cake will form on high permeability and/or high filtration pressures.
- For Crosslinked Fluids:
  - Increasing Fluid Viscosity will INCREASE the Apparent Cw by Reducing the Filter Cake Growth.
  - Increasing Temperature
    - Increase Cw
  - Increasing Breaker Concentrations
    - Decrease Cw
  - Increasing Gel Concentration
    - Increase Cw
Fluid Loss Modeling

• Must be based on lab tests under representative conditions
  – Shear, temperature, perm, pore-size, filtration pressure, age, composition, etc.

• Fluid leakoff properties can be combined numerically with reservoir properties

• Matrix leakoff is different than fissure/fracture leakoff
Multiple Simultaneous Leakoff Mechanisms

• **Matrix leakoff**
  – Controlled by reservoir properties
    • Perm, porosity, pore-size, fluid mobility, compressibility
  – Is subject to wall filter-cake control
  – Follows $\sqrt{\text{time}}$ dependent velocity profile

• **Fissure leakoff**
  – May change with fluid or net pressure
  – Is not controlled by filter-cake
  – Remains steady-state or constant rate
  – Is not dependent on reservoir matrix properties
Interaction of Fissure Opening Mechanisms

\[ \frac{\partial W}{\partial P} \]

Q_{\text{leak}}

PDL and Storage

\[ Q = T \frac{\partial P}{\partial L} \]

\[ V_p \]

\[ V_f \]

\[ \frac{\partial W}{\partial P} \approx \text{YME} \]
Spatial Location of High PDL is Important to Screenout Prediction

- High net pressure near-well, open fissures, high PDL, near-well screenout
- Low net pressure near-tip, no PDL, new surface area, high matrix leakoff

Describing PDL as only a multiple of Ct increases leakoff at the tip, not at the perfs
Leakoff coefficient at frac fluid pressures above maximum closure stress is given by:

\[ C_p = C_o e^{C_{dp} \Delta P} \]

Where:
\( \Delta P \) is pressure above fissure normal stress,
\( C_o \) is the constant matrix leakoff coefficient,
\( C_{dp} \) is the pressure-dependent leakoff coefficient
\( C_p \) is the local apparent total leakoff coefficient
Flow Through Smooth Surfaced Fracture

\[ Q = 5.11 \times 10^6 \left[ \frac{H \Delta P w^3}{L \mu} \right] \]

- \( Q \) = Flow rate (bbl/day)
- \( H \) = Height of fracture (ft)
- \( \Delta P \) = Pressure differential (psi)
- \( w \) = Fracture aperture (in)
- \( L \) = Length of fracture (ft)
- \( \mu \) = Fluid viscosity (cp)

\[ k_{\text{equiv}} = 54 \times 10^6 \ w^2; \ k \ (\text{darcies}), \ w \ (\text{inch}) \]

0.01” crack = 5400 d
Effect of Fractures on System Permeability for Parallel Flow

Assumed Fracture Aperture = 0.001”

Matrix Perm

Folds of Increase over Matrix Perm

Fracture Spacing, ft
Understanding Leakoff

- Both matrix and fissure leakoff must be considered
- Leakoff can vary in space and time
- Leakoff rate (and system perm) can be highly pressure dependent
- Post-frac production maybe tied to leakoff
- Large-scale leakoff measurements correlate better to production than small-scale (core) perms
- Effects of fluid additives and reservoir properties must be considered